HE MINERALOGICAL MAGAZINE

AND

JOURNAL OF

THE MINERALOGICAL SOCIETY

. 177 June, 1942 Vol. XXVI

A suite of volcanic rocks from south-west Uganda containing kalsilite (a polymorph of $KAlSiO_4$).

(With Plate VI.)

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[Read January 22, 1942.]

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1. Introduction.

DURING the last few years large collections of rock specimens from the Toro-Ankole volcanic fields, east and south-east of Ruwenzori, have been sent to rham by the Geological Survey of Uganda for petrological investigation. The cimens recently studied include representatives of a suite of highly potassic rabasic lavas. Some of these resemble melanocratic olivine-nephelinites or ine-rich ankaratrites, but the nepheline-like felspathoid which they contain, ead of being nepheline, is a polymorph of $KAlSiO_4$. For chemical reasons mineral was at first thought to be kaliophilite. Other types, closely related, tain leucite, biotite, or melilite, in addition to the supposed kaliophilite.

Natural kaliophilite is an extremely rare mineral and is known with certainty y from certain ejected blocks of biotite-pyroxenite and augite-melilite-ite-rocks from Monte Somma (Bannister, 1931, p. 569). Hitchcock (1900, 7) recorded 'a multitude of acicular crystals of kaliophilite' from pegmatitoid occurring in a Hawaiian nepheline-olivine-melilitite, but provided no ce for his identification. The pegmatitoids have since been exhaustively ied by Dunham (1933, p. 372), who finds the only acicular crystals present

to be apatite and hydronephelite. I am indebted to Dr. Dunham for his opi that Hitchcock's 'kaliophilite' is almost certainly hydronephelite.

As neither kaliophilite nor any other polymorph of $KAlSiO_4$ had previo been detected as a constituent of volcanic rocks, it was obviously desirable the mineral in question should be studied by X-ray methods. I was fortu in being able to enlist the expert co-operation of Mr. F. A. Bannister, who skilfully and successfully tackled the very difficult problems involved in such intricate investigation. Mr. Bannister's results, supplemented by micro-chem analyses made by Dr. M. H. Hey, are recorded in the communication w follows this paper. The new data indicate that the mineral is not kaliophi but a hitherto unrecognized polymorph of $KAlSiO_4$ for which the appropria mnemonic name *kalsilite* is proposed. The present communication is devote the mode of occurrence and petrology of the newly discovered kalsilite-bea lavas.

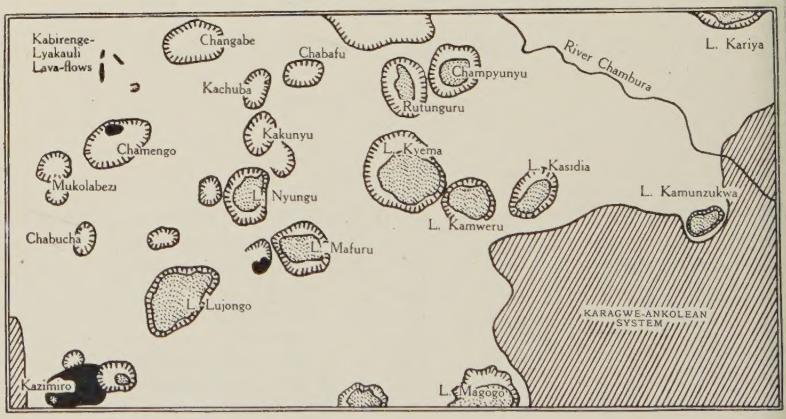


FIG. 1. Sketch-map showing the explosion craters and lava occurrences of part of Bunyaruguru volcanic field of south-west Uganda. The area illustrated is $7\frac{1}{4}$ by $3\frac{3}{4}$ m Topographical and geological details from an unpublished field map by A. D. Cor Geological Survey of Uganda.

Karagwe-Ankolean system—inclined shading; lava occurrences—black; tuffs—unsha crater lakes—dotted.

Field work in the Toro-Ankole volcanic areas was begun in 1929 by Wayl and Combe (Combe, 1930), and a preliminary account of the tuffs, ejected blo and bombs then collected was published a few years later (Holmes and Harwo 1932). During the 1932, 1933, and 1938 seasons more extensive and system geological exploration was carried out by Combe, and some of his observati have been briefly described in the Annual Reports of the Survey (Combe, 19 1934, and 1939). Detailed accounts of the isolated Katunga volcano and rocks have also appeared (Combe, 1937; Holmes, 1937).

The specimens now to be considered are from the volcanic area of Bunya guru, which stretches southwards from the south shore of Lake George, pa over the floor of the western Rift depression and partly over the adjacent plat to the south and east of the Rift. The area, part of which is shown in fig.

typical field of multiple vents, characterized by closely spaced explosion
ters of late Pleistocene to Recent age, many of which are now occupied by
es. The vents have been drilled through sediments—locally more or less
tamorphosed—of the Karagwe-Ankolean system and, in many cases, through
overlying mantle of 'older' tuffs, dating from the Middle Pleistocene, the
canic topography of which has been largely obscured by the later explosions.
e Karagwe-Ankolean rocks, which contribute abundantly to the tuffs and
canic breccias, are mainly argillites or phyllites, accompanied by grits and
artzites. Ejected blocks of limestone occur in the tuffs about the craters of
kes Mafuru, Kamweru, and Kasidia and probably represent impersistent
ticles of limestone in the Karagwe-Ankolean (Combe, 1934, p. 65; 1939, p. 19),
ce the occurrences lie along a line that is roughly parallel to the regional strike
the Karagwe-Ankolean formations. To the east and south of the volcanic
a there are widespread exposures of granite (Simmons, 1939). Ejected blocks
m several of the vents, e.g. those of Lake Nyungu and Chamengo, indicate
t similar granite also occurs locally beneath the volcanic area.

Occurrences of lava in bulk are known in only four localities: Kabirengè-
akauli, Chamengo, Mafuru, and Kazimiro (see fig. 1). The western of the two
furu craters truncates what appears to be a lava flow. The latter and most of
ejected blocks of lava found in and around the Mafuru craters are composed of
ew rock-type composed of olivine, pyroxene, kalsilite, perovskite, and black ore.
llowing current fashion, the rock could be called 'olivine-rich mela-kalsilitite',
as leucite and biotite varieties also occur and require distinguishing names,
h a term would be unduly awkward. The name *mafurite* is therefore proposed
the new type, and the varieties alluded to then become *leucite-mafurite*
biotite-mafurite respectively. As ejected blocks, biotite-mafurite also
urs in and about the crater of Lake Nyungu. *Melilite-mafurite* is found as
cted blocks in and near the crater of Lake Kamunzukwa, which lies about
r miles to the east of Lake Mafuru. On the north-west side of Chamengo crater
truncated edge of a dome- or plug-like mass is exposed (Combe, 1934, pp. 66
68). The specimens representing this lava-dome range from mafurite poor
eucite, through leucite-mafurite to *kalsilite-ugandite*, ugandite being melano-
itic olivine-leucitite (Holmes and Harwood, 1937, p. 11).

Apart from the local occurrences of lava mentioned above, the volcanic pro-
cts are pyroclastic. The dominant volcanic material of the tuffs, represented
well-preserved, essential and accessory, lapilli and occasional bombs and
cks, is *katungite* (potash-rich olivine-melilite lava: Holmes, 1936 and 1937).
pilli of *kalsilite-katungite* have recently been detected and are described on
210. Ugandite, mainly the olivine-rich variety, also occurs, sparingly as
illi in some of the tuffs and more conspicuously as ejected blocks and bombs.
e of the latter, from the old rest-camp of Kichwamba, adjoining Kachuba
ter, has already been described under the name melanocratic olivine-leucitite
olmes and Harwood, 1932, p. 415).

The following classification shows the mineralogical relationships of the
canic rocks of Bunyaruguru, with the exception of one or two rare olivine-free
es, of which *proto-katungite* (mineralogically like katungite, but without
rite) is the chief.

TABLE I. Kalsilite- and leucite-bearing volcanic rocks of Bunyaruguru, south-west Uganda.

Olivine, Perovskite, and Black ore +	Leucite	Leucite > Kalsilite	Kalsilite > Leucite	Kalsilite
Augite	Olivine-rich ugandite UGANDITE	Kalsilite-ugandite	Leucite-mafurite	MAFURITE Biotite-mafurite
Augite > Melilite	Melilite-ugandite (Melilite-poor alnöite)	—	—	Melilite-mafurite
Melilite > Augite	(Alnöite)	—	—	—
Melilite	Leucite-katungite KATUNGITE* Biotite-katungite		Kalsilite-katungite	

*Leucite is rarely developed in katungite, but computed estimates of the composition the glass indicate that, on an average, the glass is potentially leucitic, being slightly silicic in two examples and slightly more in a third.

The tuffs also invariably contain mineral fragments and ejected blocks a cognate sub-volcanic suite of rocks composed essentially of one or more of minerals biotite, augite, and olivine, and comprising such types as glimmer biotite-pyroxenite, and biotite-peridotite. As elsewhere in the Toro-Ank fields, these rocks are of earlier formation than any of the volcanic types, si they invariably appear in the latter as xenoliths and xenocrysts in various sta of corrosion and disintegration.

2. SOURCES OF MATERIAL.

The Mafuru craters.—Lake Mafuru is of elliptical outline, about 600 ya long by 100 yards across. Immediately to the west of the lake crater, separated from it by a narrow rib about 70 feet high, is an older dry cra about 300 yards long by 100 across, which is open at its south-western e where it is truncated by a swampy depression that extends towards L Lujongo. The surface of the water in the lake crater is lower than the floor of dry crater. Reporting on his first visit, Combe (1934, p. 66) writes: 'The so wall of the older crater is about 400 feet high and is formed mostly of tuffs agglomeratic rocks. About half way up is a sheet of lava exposed for a thick of 15 feet or so, but the bottom is not seen. The lava can be observed for a len of about 70 feet along the crater wall but it probably extends farther.' In 1 Combe again visited the crater and found that much clearing had been don a preliminary to banana cultivation. The lava sheet was then seen to ext along the wall for at least 150 yards, the exposed thickness increasing f 6 feet at the eastern end, near the rib, to about 120 feet at the western end.

per part of the sheet is scoriaceous and slaggy and is overlain by 30 feet of tuff
l agglomerate packed with ejected blocks of various types of mafurite up to
eet across. The upper surface of the lava was not exposed, a 20-foot slope of
ck soil intervening between the highest exposure of lava and the lowest of
overlying tuffs. It was observed, however, that the top of the sheet drops
height towards the west, suggesting that it originated from a source in the
ection of the lake crater.

The following specimens were collected serially from bottom to top of the
posures towards the western end of the sheet. It will be noticed that leucite-
furite is represented as well as mafurite.

t.

Highest exposure of tuffs:

C.6078 Ejected block of mafurite with glassy base.
C.6077 Katungite-tuff.

Lowest exposure of tuffs:

C.6076 Ejected block of mafurite.
C.6075 Katungite-tuff (containing lapilli of mafurite, some of which are enclosed in katungite lapilli).
C.6074 Katungite-tuff (containing lapilli of leucite-mafurite).
C.6073 Ejected block of mafurite.

Highest exposure of lava sheet:

C.6072 Scoriaceous mafurite, typical of the upper 25 feet.
C.6071 Altered mafurite with irregular spidery vesicles.
C.6070 Altered leucite-mafurite with irregular vein-like vesicles.
C.6069 Altered mafurite riddled with vermicular vesicles.
C.6068 Mafurite with a finely vesicular band.
C.6067 Leucite-mafurite.
C.6066 Mafurite from lowest exposure of lava sheet.

elatively coarse-grained mafurite from blocks fallen from an exposure of the
e sheet at the north end of Ndeke Ridge, immediately south of the dry crater,
presented by C.6143.

ther specimens of the tuffs and ejected blocks of Mafuru are listed below:

Locality.	Katungite tuffs.	Ejected blocks.	
wall of lake crater ...	C.4071	C.4069	Biotite-mafurite
		C.4070	Glassy mafurite
		C.4078	Biotite-mafurite
		C.6051	Biotite-pyroxenite
rim of lake crater ...	C.6037 (katungite poor in olivine)	C.6042	Mafurite
all of lake crater, 75 feet low rim	C.6043 (abundant lapilli of proto-katungite)	C.6045	Biotite-pyroxenite
between the craters ...	C.6079 (contains mafurite enclosed in katungite)		

ake Nyungu crater.—The crater occupied by Lake Nyungu is situated to the
h-west of Lake Mafuru. On the north side the wall rises only 60 feet above the
r level, but towards the east it rises to over 200 feet and on the other side
bout 150 feet. From the NE. corner cliffs about 30 feet high can be followed
the eastern side, and above and below this main exposure smaller outcrops

can be traced along the steep crater wall. These are all of katungite tuffs volcanic breccias containing abundant fragments of quartzite, fewer of phyl occasional blocks of granite, and sporadic blocks of biotite-mafurite and oliv rich ugandite. The specimens studied are as follows:

Locality.	Katungite tuffs.	Ejected blocks.
NE. wall of crater, 40 feet above lake	C.4046	C.4042–45 Biotite-mafuri C.4047 Olivine-rich ugand
Road cutting, E. of crater, 200 feet above lake	—	C.4049 Mafurite
Road cutting, NW. of crater	C.4066–67	
SW. flank of crater	C.6135 (contains leucite-katungite and kalsilite-katungite)	
50 feet below SE. rim of crater	C.6136	

Chamengo crater.—Chamengo crater (Combe, 1934, pp. 67–68) is of ellipt outline, the floor being about 350 by 120 yards. The walls are of layered t except on the NW. side, where the wall reaches its maximum height of 250 f Here, under a 100-foot cover of tuffs, crags of dark massive lava, with a talu fallen blocks at the base, can be seen up to a height of 150 feet. At its west end the lava cuts sharply across the tuffs. The occurrence is interpreted Combe as a plug- or dome-shaped mass that failed to break through to the surf but was subsequently exposed by the explosions responsible for the present cra

Although in the field the lava-dome appears to be of homogeneous composit the three specimens collected from its outcrop are only superficially al C.4006 is mafurite with traces of leucite, C.4007 is leucite-mafurite, and C.4 is kalsilite-ugandite with much more leucite. It is noteworthy that the ejec blocks lying on the surrounding tuffs are identical with C.4008. The associa tuffs and blocks are as follows:

Locality.	Katungite tuffs.	Ejected blocks.
S. wall of crater	C.4002–4 (containing ugandite and mafurite)	C.4005 Kalsilite-ugandite
Foot of rift escarpment, NW. of crater	—	C.4805 Kalsilite-ugandite (containing olivine-leucit
Above the lava-dome ...	C.5995	

Lake Kamunzukwa crater.—Lake Kamunzukwa crater lies about four m east of Lakes Mafuru and Nyungu, near the SE. margin of the volcanic a At its SW. corner the lake drains by way of a small stream into the Lub which is a tributary of the Chamburu river. The Karagwe-Ankolean formati that border the crater on three sides are mainly blue-grey phyllites, and n of the accidental blocks of tuffs are of similar material. The specimens avail for study are as follows:

Locality.	Katungite tuffs.	Ejected blocks.
SW. shore of lake	C.3519 C.3520 (contains melilite-mafurite)	C.3521 Melilite-mafurite
Near outlet of lake	C.6109	C.6107–8 Melilite-mafuri

3. Mafurite.

The specimens from the lower exposure of the Mafuru lava and those of the ted blocks derived from it are compact, fine-grained porphyritic rocks of r colour, containing abundant phenocrysts of lustrous light-green olivine, r 2 mm. long, and occasional xenocrysts of olivine, biotite, and augite up to 5 mm. across. Other xenolithic inclusions, of all sizes up to 2 cm., consist of ite-pyroxenite, glimmerite, and biotite-peridotite in various stages of resorp-, some of them being brightly crystalline, while others are dull black with owish spots and margins. Xenoliths of phyllite have been detected, but are emely rare and very small. Oval and somewhat porous light-coloured patches, to 1·5 cm. long, occur sporadically. These are found under the microscope be segregations of coarser crystallization of the type to which the term gmatitoids' has been given by Lacroix (1928). Vesicles are rare, such as occur being irregular cavities, 1–4 cm. across, lined with calcite and zeolites, uding phillipsite. About fifty feet above the lowest exposure small vermi- r vesicles with similar linings become conspicuous (C.6069); 30 feet higher rock is scoriaceous (C.6072) and most of the cavities are free from linings. se specimens are internally altered and have a fawn or brownish hue, with ge or reddish-brown pseudomorphs after olivine, and brick-red altered oliths of biotite-pyroxenite.

n section the minerals found are those listed in table II. The micrometric surements were made on sections free from xenoliths and pegmatitoids. rt from the altered specimens just referred to, the rocks are beautifully fresh of uniform composition and texture, xenoliths and pegmatitoids being rarely ountered except in sections specially cut to reveal their characters. A typical l is illustrated in pl. VI, fig. 1.

Table II. Mode of Mafurite, C.6073.

	Volume %.	Average grain-size.
Phenocrysts:		
Olivine	20·6	1·2 mm.
Diopside and augite ...	6·3	0·9
Groundmass:		
Diopside	26·0	0·07 × 0·01
Kalsilite	23·7	0·12
Perovskite	6·2	0·02
Black ore	5·7	0·03
Olivine	4·4	0·07
Biotite	2·3	0·25
Glass	4·1	—
Apatite	n.d.	—
	99·3	

Olivine occurs as somewhat rounded euhedral phenocrysts, some of which, ecially the larger examples, are deeply corroded and even eviscerated by ges of groundmass material crowded with black ore and perovskite. From ds of the tongues strings of isolated grains of ore continue into the olivine. asional polysomatic aggregates of olivine occur and are penetrated by similar ges, generally along intergranular boundaries. Such aggregates are probably

xenolithic, as they are commonly traversed by tiny replacement veinlet
biotite and by sinuous trains of gas bubbles like those in the olivine of the per
tite xenoliths and ejected blocks of the area (cf. Holmes and Harwood, 1
p. 21). In all cases the olivine is optically negative, but with a nearly stra
isogyre in β-sections. Inclusions of ore, and less commonly of perovskite,
confined to a marginal zone, except for rare internal groups of these mine
which probably mark the terminations of penetrating tongues. In the grou
mass, olivine occurs as tiny blebs. Throughout the whole suite of mafurite
its varieties no trace of serpentinization has been detected.

Pale-green *diopsidic augite* is present as stumpy euhedral microporphyr
crystals, some of which contain irregular or corroded cores of bright or grey
green augite identical with the pyroxenes of the ejected blocks of peridotite
biotite-pyroxenite. Large xenocrysts and aggregates of these augites also oc
sparingly, in every case bordered in optical continuity with a narrow fringe of
diopsidic type normal to the rock. In the groundmass the same type of diops
augite is present as microliths which are generally crowded together, either
an open felt or in stream-lined swarms.

Perovskite is conspicuously and uniformly distributed through the groundm
as golden-brown or yellow octahedra and twinned groups, and as greenish-yel
grains of smaller size. Black ore, probably *titaniferous magnetite*, also occ
abundantly as octahedra and grains.

Kalsilite forms a clear interstitial background of anhedral to subhedral crys
which poikilitically enclose the above-mentioned minerals of the groundm
together with rare minute needles of apatite. In a fallen block from the Maf
sheet, C.6143, there are streaks of relatively coarse grain in which poikil
kalsilite is unusually conspicuous and sometimes euhedral. A similar variety
mafurite occurs as lapilli in the tuffs above the sheet (pl. VI, fig. 2). In the norm
finer-grained type, the kalsilite background is interrupted here and there
patches of slightly turbid glass. Kalsilite generally occurs as stout prisms,
in some specimens—especially those of the more glassy varieties—the prisms
longer and have skeletal terminations like double-pronged forks; the 'pron
often consist of parallel bundles of fibres of which the outermost are the long

Adjacent to olivine the kalsilite occasionally merges almost imperceptibly in
ragged patches of phlogopitic biotite, pleochroic from faintly greenish-yellow
pale reddish-brown. The mica is clearly a synantetic mineral and its occurre
where kalsilite and olivine would otherwise meet first suggested the possibil
that the nepheline-like mineral might be kaliophilite. Moreover, it was noti
that where the mineral is in contact with pyroxene and black ore no sign
aegirine appears, as might be expected if it were nepheline. From the chemi
composition and norm of mafurite it became certain that the nepheline-l
mineral contains very little soda, and that chemically it is probably a potassi
end-member of the nepheline series. The analysed rock contains 6·98 % of K
and only 0·18 % of Na_2O. As the potash must be almost entirely in biotite, gl
and the mineral under discussion, it can easily be estimated that the lat
contains at least 25 % of K_2O. As a further check on the chemical identity
the mineral, a small sample of a pegmatitoid occurring in mafurite from Nyun
crater (C.4049) was submitted to Dr. H. F. Harwood for determination of
alkalis. The sample contained rather more diopside than kalsilite and also

e calcite. The results were K_2O 11·37, Na_2O 1·33 %. Pure kalsilite contains % of K_2O.

inally, X-ray and micro-chemical investigation of the separated mineral by nister and Hey (recorded in the paper that follows) led to its recognition as lymorph of $KAlSiO_4$ which differs in its cyrstal-structure from both nepheline kaliophilite. A distinctive name being therefore necessary, *kalsilite* is pro- d. Optically, kalsilite cannot be distinguished from nepheline, the refractive es being about the same or slightly higher than that of Canada balsam. separated material Bannister obtained the values ω 1·542, ϵ 1·537±0·002; e are higher by about 0·01 than the corresponding values for kaliophilite nister, 1931, p. 601).

pegmatitoids (Lacroix, 1928; Dunham, 1933) are segregations of pyrogene rals occurring in veins, cavities, lenticles, and streaks in basic volcanic rocks, hich they bear a relationship analogous to that of the pegmatites associated plutonic rocks. The minerals are generally the same as those of later crystal- ion in the enclosing rock, but of coarser grain; with them zeolites and calcite be associated, representing a later hydrothermal phase in the cooling history. mafurite the pegmatitoids occur as lenticles, sometimes slightly cavernous rusy, most of which contain (in order of crystallization) diopside, kalsilite, calcite. Except that it may be heavily charged with tiny globular inclusions w refractive index, the diopside is identical in its properties with that of the sing rock. Euhedral crystals are characteristic, having about the same size ie microporphyritic diopside of the rock, but aggregates of subhedral forms groups of slender prisms are also common. In one case (C.4007, Chamengo) liopside is entirely of microlithic habit and associated with a little biotite. the walls, which are generally lined with diopside, the latter mineral contains inclusions of black ore and perovskite. Kalsilite increases in abundance rds the interior, where it forms continuous masses of euhedral crystals and dral grains, the former being stumpy prisms giving nearly square or hexagonal ons up to about 0·2 or 0·3 mm. across (pl. VI, fig. 3). In the diopsidic areas lite is interstitial. In turn, calcite is interstitial to both diopside and kalsilite, near the middle it may occur in patches 1 or 2 mm. across. Occasionally a phillipsite is associated with the calcite.

a few examples phlogopite or biotite occurs interstitially in addition to the rals normally present (pl. VI, fig. 4). In others both mica and olivine may und, the olivine being of early formation and confined to the walls of the atitoid. The coarse variety of mafurite (C.6075 and C.6143) is remarkable ntaining globular or lenticular inclusions of exceptionally fine grain, com- l of a background of kalsilite and rare phlogopitic biotite, which is crowded blebs of olivine, granules of perovskite, and sporadic grains of dark-green e and black ore. The paucity of the usual diopsidic augite is a notable re. These granulitic inclusions are probably related to the pegmatitoids. ar granulitic areas, but almost devoid of black ore, occur in parts of an wise normal pegmatitoid found in C.6073. Another example, occurring in ne rock, is unusually rich in black ore; it has a rim of kalsilite and pale ide, and merges imperceptibly into the groundmass of the rock.

noteworthy that the vesicular specimens from the upper part of the Mafuru are free from pegmatitoids. The *vesicles* of mafurite are generally thinly

encrusted with zeolites and calcite. Phillipsite can be detected in small radi
groups, often forming spherules, but the chief zeolite has not been ident
It occurs in globular groups of prismatic crystals and has properties like t
of heulandite, but with refractive indices below 1·497. The vesicular varieti
mafurite are internally altered. Olivine is rimmed with iddingsite, fibres of w
penetrate the crystals at right angles to the edges. Kalsilite becomes clo
and fibrous isotropic material commonly occupies the interstices betwee
other minerals.

The *xenoliths* in mafurite include the following varieties:

(*a*) Biotite-pyroxenite of the same type as the associated ejected b
(C.6045 and C.6051). These are coarse-grained and consist of green augite
biotite with accessory black ore and sphene. For an analysis of a similar va
from Katwe, north of the Kazinga Channel, see Holmes and Harwood, 1
p. 30. The dull black xenoliths already mentioned are altered biotite-pyrox
in which the biotite is mainly represented by black ores and obscure cl
by-products, while augite has become turbid through separation of minute
specks. The yellowish spots and rims of these xenoliths are found to consi
iron-stained isotropic material, the spots being bulbous areas connected wit
rims by intergranular channels. Both biotite and augite have contributed t
isotropic material, and from parts of the latter acicular diopside, min
granular olivine, and an interstitial zeolite, probably phillipsite, have crystall

(*b*) Glimmerite and olivine-bearing glimmerite with a little augite. The
xenoliths are altered examples of the latter type in which the biotite is p
changed to black ore, but mainly to deep reddish-brown iddingsite identical
that which rims the olivine phenocrysts of the enclosing rock (C.6070).

(*c*) Biotite-peridotite and small olivine aggregates. In some cases the ol
is replaced by biotite along intergranular channels communicating with
groundmass of the enclosing rock. Alteration to iddingsite is again see
examples from the vesicular specimens.

(*d*) Karagwe-Ankolean sandy argillite or phyllite. Such material is rare
when found is generally surrounded by a turbid grey isotropic zone of
refractive index. Small patches of similar isotropic material are occasio
seen in thin sections and are probably vitrified or transfused scraps of pelitic or

Chemical composition.—The results of an analysis of mafurite (sample
from megascopic xenoliths and pegmatitoids) are listed under C in table
(p. 212). The 'norm' (table IV) is calculated with priority given to diop
after computing the minor constituents, so that some approach to the mo
attained. It will be noticed that leucite appears as a normative constitu
although no trace of leucite can be detected in the analysed specimen. Th
partly accounted for by the presence of biotite and glass in the rock, and pa
perhaps, by the inclusion in the analysed sample of scraps of pelitic or
siliceous material too small to be seen in the hand-specimen. In this and
'norms' similarly calculated (table IV) perovskite is much lower than the m
amount, ilmenite being correspondingly high. Suitable correction for this
crepancy would liberate FeO (at the expense of CaO) for distribution bet
diopside and olivine.

The rock differs from all the previously analysed rocks from the Toro-Ank
province (Holmes and Harwood, 1932; Holmes, 1937) in its exceptionally

and low Na_2O. No close analogues from other regions have been traced. her discussion and comparisons are deferred to a later section (p. 211).

4. Biotite-Mafurite.

ost of the specimens of mafurite contain a little interstitial biotite, the ortion being less than about 5 %. Certain ejected blocks from Mafuru and gu are, however, conspicuously richer in biotite and are therefore distin- d as *biotite-mafurite*. The specimens of this type have a general resemblance ose of mafurite, but are of brownish-grey colour. Olivine is invariably coated iotite and consequently looks yellow-brown, except on freshly broken es. Small xenocrysts of biotite and xenoliths of glimmerite are common, inclusions of altered phyllite and mica-schist are more conspicuous than afurite.

section (pl. VI, fig. 5) the minerals are seen to be almost the same as those afurite and it will suffice to draw attention only to the differences, which mainly those of proportion and habit. Microporphyritic diopsidic augite, with bright green pleochroic cores, is less abundant, and in some specimens rare; microliths and small bladed prisms, however, make up a higher pro- ion of the groundmass. Biotite is uniformly distributed as ragged interstitial hes with γ 1·580; as a 'reaction' mineral bordering and penetrating olivine; as small euhedral crystals. It constitutes about 15 % of the rock. Perovskite s abundant, and black ores, which must be highly titaniferous, judging from hemical composition, are more thickly distributed, especially as inclusions ivine. The interstitial background contains a higher proportion of pale- n fibrous isotropic material, probably glass, which clears to kalsilite over derable areas. Kalsilite also occurs as small laths, often with forked skeletal inations. The analysis of C.4043 suggests the presence of a little nosean, none has been detected.

gmatitoids are small and very different from those already described from rite. One type (C.4069) is lined with tangential, radial, and criss-cross blades otite, rare radiating groups of diopside microliths, and innumerable needles batite; all embedded in calcite, which entirely occupies the interior, except little fluorite. C.4078 contains many micro-amygdales of calcite; some of , transitional to pegmatitoids, have biotite growing in from the walls. her type of pegmatitoid, developed on a microscopic scale only, consists st wholly of kalsilite, with rare prismoids of diopside against the walls.

noliths, as already indicated, are mainly of glimmerite, the biotite of which γ 1·631 and is thus of different composition from the new biotite of the ndmass. Biotite-peridotite occurs sparingly and, as in mafurite, xenolithic gates of olivine are common. Among the pelitic inclusions, a much corroded ent of mica-schist (in C.4069) shows some features of interest. The original e is a dull, pale-brown, bleached-looking variety, but towards the margin xenolith it is made over to a variety closely resembling that of the enclosing Surrounding the xenolith is a zone of turbid isotropic material in parts of pockets of zeolites occur, together with prismoids of diopside and rounded s of leucite. Within the schist, which is penetrated by tongues of ground- , he felsic constituents are locally replaced by streaks of similar turbid rial, clearing here and there to zeolites.

Chemical composition.—An analysis of a typical specimen of biotite-maf from Nyungu has been made by Dr. H. F. Harwood and is recorded und in table IV. The 'norm' is calculated as before to give the maximum am of diopside. The analysis is closely similar to that of mafurite. The slig higher SiO_2 and the higher proportion of normative leucite reflect the hi biotite and glass contents of the rock, and may also be symptomatic of tamination by pelitic inclusions, such as the mica-schist described above.

5. Leucite-Mafurite and Kalsilite-Ugandite.

The leucite-mafurite (C.6067) of the Mafuru lava-sheet is megascopi indistinguishable from the associated mafurite, while C.6070 is an altered va showing the same modifications as altered mafurite. Under the microscope only new feature is the presence of rounded grains of leucite in the groundm These are often turbid and of pale buff colour: in the altered rock entirely There can be little doubt that leucite has developed as the result of the incorp tion of a small proportion of pelitic or siliceous material. C.6067 contains s xenoliths of phyllite changed marginally, like the mica-schist in biotite-mafu to a buff-coloured isotropic substance of low refractive index which clo resembles the altered leucite of the groundmass. One example is riddled tongues of groundmass and is now almost entirely represented by isotr material containing patches of which some are crowded with olivine grains zeolitic matrix, others with diopside granules, and others, reminiscent of reso biotite, with grains of black ore.

The leucite-mafurite (C.4007) and kalsilite-ugandite (C.4008) of the Cham lava-dome are fine-grained blue-grey rocks containing sparse phenocryst yellow-green olivine, up to 5 mm. across, but generally much smaller; s small blades of augite; and occasional xenocrysts of biotite. In section these r are seen to be members of a continuous series, differing only in the rela proportions of leucite and kalsilite. C.4007 contains abundant microporphy crystals of olivine and pale-green diopsidic augite in a groundmass whic exactly like that of mafurite, but with the addition of small, sparsely distrib grains of clear leucite. A narrow ill-defined band occurring in one slide cont larger and more abundant leucites and is identical with the kalsilite-ugan described below. Poikilitic patches of biotite occur sporadically, in each moulded around numerous blebs of olivine, and also including microlith diopside and granules of perovskite and black ores. The specimen cont excellent examples of pegmatitoids of the normal type, with marginal concen tions of diopside surrounding aggregates of euhedral kalsilite.

The rocks to which the term kalsilite-ugandite is applied (C.4005 and C.4 contain much more conspicuous leucite and would at first sight be called ugan The interstitial material, however, though not abundant, is largely compose kalsilite in tiny poikilitic areas, some of which are euhedral, the kalsilite b interrupted here and there by biotite and fibrous buff-coloured glass. Leu occurs as colourless grains, generally about 0·1–0·2 mm. across, and in clus of similar or even larger grains which may exceed 1 mm. in diameter. H again, there is evidence that the leucite owes its existence to silica introduce pelitic xenoliths. One of the latter is now represented mainly by turbid isotr material containing biotite, diopside granules, and a zeolite. It is surroun

ut any definite boundary, by a zone of groundmass which is highly charged minute grains of leucite.

1805, occurring in the tuffs near the foot of the neighbouring Rift escarpment, ntical in all respects with C.4005. It is of interest in containing vaguely ed inclusions of beautifully fresh olivine-leucitite and ugandite.

emical composition.—The results of an analysis of leucite-mafurite, C.4007, ted under E in table III. The 'norm', in table IV, is calculated as in the ous cases. Comparison with C shows that the composition is close to that afurite, except for higher Na_2O and much lower K_2O, in which respects it aches that of melilite-ugandite, G. The most striking difference between norms' of mafurite and leucite-mafurite is the fact that mafurite, with no hi leucite, has much more normative leucite than leucite-mafurite. The most able explanation of this discrepancy is that the analysed sample of mafurite have been slightly contaminated by silica-rich xenolithic material. A determination of the alkalis in kalsilite-ugandite, C.4008, gave Na_2O 1·12 and K_2O %.

6. Melilite-Mafurite.

far, this variety has been found only as ejected blocks and accessory lapilli rring in the katungite-tuffs of Lake Kamunzukwa crater. The blocks are ark-grey porphyritic lava, containing small phenocrysts of yellow-green ne in a very fine-grained groundmass. Xenolithic inclusions are more dant than in mafurite, and include xenocrysts of biotite, up to 1 cm. across, of olivine and augite in smaller grains, together with aggregates of these rals, singly and in combination, glimmerite and biotite-pyroxenite being characteristic. Phyllite of the type exposed around the crater also occurs dically.

section, the rocks differ from mafurite in the following respects. Biotite is nt only as xenocrysts. The margins are corroded and heavily sprinkled with ores in a matrix which, though generally obscure, can here and there be to contain minute grains of olivine and calcite in an isotropic base. The dmass consists of an interlacing network of diopside prismoids, accompanied rains of perovskite and black ore and rare blebs of olivine, together with laths of melilite (up to 0·2 by 0·04 mm.) and stumpy or elongated forked s of kalsilite (0·04 mm. across); poikilitic patches of kalsilite, interspersed cloudy glass, occupy the interstices. The melilite shows low but normal ization colours and is optically negative. In C.6108 it is largely altered to a v isotropic substance comparable with the yellow pseudomorphs after te described by Brauns (1922, p. 35) from the melilite-nephelinite of ebacher Ley in the Eifel.

y amygdales, interconnected by veinlets, are occupied by calcite, either , or followed internally by radial groups of phillipsite. In one larger example ide prisms have grown inwards from the walls and now lie in a matrix of ; nothing else suggestive of pegmatitoids has been detected.

the xenolithic constituents only phyllite calls for further mention. One or n all corroded fragments with turbid isotropic rims may be seen in most ; most of the smaller ones are entirely isotropic. The material has a refractive ell below that of Canada balsam and contains black ore and patches of a birefringent zeolite.

Chemical composition.—An analysis of melilite-mafurite is presented und in table III. As would be expected, the rock is intermediate in compos between katungite and mafurite (cf. fig. 2). As before, the 'norm' is calculat give the maximum amount of diopside, a procedure which in this case inv allotting all the K_2O to normative kaliophilite, since Ca_2SiO_4—symptomat melilite—also appears.

7. Kalsilite-Katungite.

In some of the katungite tuffs from the Kabirenge valley west of Chan crater (C.5953 and C.5962), and in others from the NW. wall of the crater (C.4011–12), beautifully preserved lapilli of kalsilite-katungite have been fo associated with others of ordinary katungite. Similar lapilli occur in the tu Mukolabezi crater SW. of Chamengo (C.5999), Nyungu crater (C.6135), Lake Chuwera crater (C.3498).

The lapilli consist of olivine, melilite, kalsilite, perovskite, and black or a greenish-yellow glass which is interrupted in some occurrences by mi round or sinuous amygdales containing phillipsite (pl. VI, fig. 6). Olivi present partly as irregular xenocrysts, derived from biotite-peridotite, fragm of which also occur, but mainly as well-developed euhedral crystals. Mel occurs as tabular crystals which appear as sharply defined laths and occas eight-sided sections. Polarization colours are low but normal, and the op character is negative. Minute inclusions of perovskite and kalsilite ca detected. In some of the lapilli the melilite is altered, by development of f normal to the base, to a highly birefringent product which is probably cebo Kalsilite has crystallized as prisms with forked terminations and the form optical properties are identical with those of kalsilite of similar habit in mafu Golden-brown perovskite is very conspicuous as octahedra and twins a often concentrated around the microphenocrysts of olivine. Black ore developed only sparingly and is more abundant as inclusions in the xenoc of olivine.

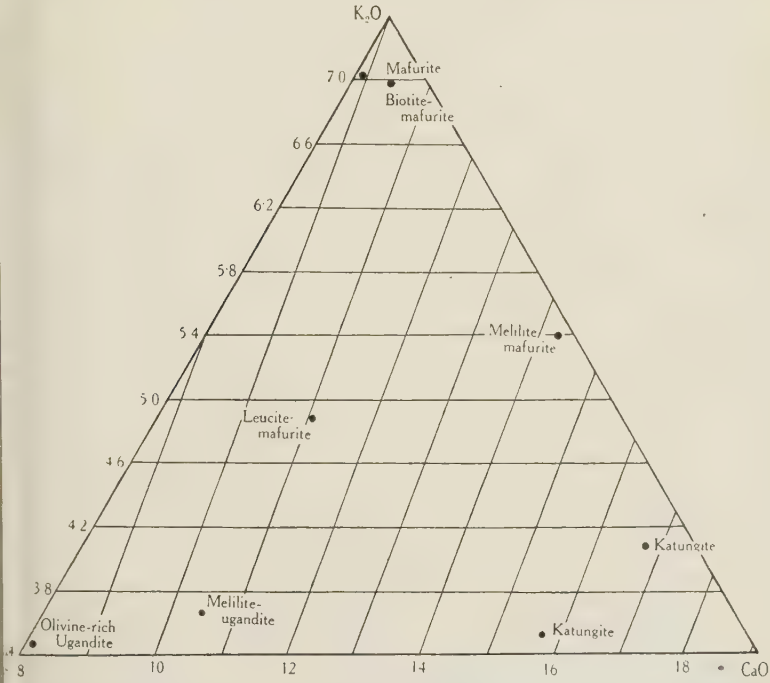
In the description of the type katungite of Katunga (Holmes, 1937, p. nepheline was recorded, with the reservation that 'it may be kaliophilite'; in the definition of katungite (p. 210) kaliophilite was listed as one of the pos potash minerals. For 'kaliophilite' kalsilite should now be read. It is of interest that kalsilite-katungite is the only rock type so far recognized in wh polymorph of $KAlSiO_4$ (whether kaliophilite or kalsilite) occurs without dio or augite. It thus represents one of the most ultrabasic silicate rocks could exist.

8. Relationships.

Mineralogical.—The classification tabulated on p. 200 clearly shows mineralogical relationships of the olivine-bearing volcanic rocks of Bunyaru The main types are distinguished by the following pairs of the four cr minerals: augite, melilite, leucite, and kalsilite.

Ugandite	= Augite + leucite	with abundant olivine, perovskite, and black ore
Mafurite	= Augite + kalsilite	
Katungite	= Melilite + leucite or leucitic glass	
Kalsilite-Katungite	= Melilite + kalsilite	

here is continuous transition between ugandite and mafurite and probably ween katungite and kalsilite-katungite. Augitic varieties of the latter are as unknown, and augitic katungite is very rare. The gap between katungite ugandite is chemically bridged by a series of alnöites from Katwe crater of Bunyaruguru) which are heteromorphous equivalents of augite-katungite melilite-ugandite, according as the proportion of melilite present is greater s than that of augite. Lapilli of melilite-poor alnöite also occur in the tuffs



2. Triangular part of a field of co-ordinates representing percentages of K_2O (horizontal) aO (inclined) to illustrate the relationships between katungite, mafurite, and olivine-gandite and transitional varieties between these three 'corner' types. Biotite-mafurite esented by the dot just above $K_2O = 7$.

amakumba crater (in Bunyaruguru, but north of the area portrayed in). Transitions between the melilite-bearing varieties of ugandite and ite—that is to say, rocks containing all four of the critical minerals—have een detected, but there seems to be no theoretical reason for supposing ch rocks do not exist. Other possibilities of heteromorphism are discussed

mical.—The chemical relationships can be gathered from inspection of III and IV, in which analyses of the mafurite series and related rocks are in the order of the same rocks as plotted in fig. 2; that is, from katungite, ough the mafurite series, B, C, D, and E, to the ugandite series, F and G, k to katungite, H. The analysis representing ugandite is that of an ich example, F, from Kachuba crater, which is typical of the variety

most characteristic of the area. Melilite-ugandite occurs in intimate associ with olivine-rich ugandite at Kachuba and Kazimiro; an analysis of this va G, is presented here to complete the suite. H is a new analysis of katungite Chamakumba crater, where the rock occurs as bombs and lapilli in katu tuffs; associated bands of tuff contain lapilli of an alnöitic type, and of p katungite and melilite-ugandite.

TABLE III. Chemical composition of the Mafurite series (B–E) and related rocks, Bunyaruguru, SW. Uganda.

	A.	B.	C.	D.	E.	F.	G.
SiO_2 ...	35·37	37·05	39·06	40·00	39·28	40·47	38·62
Al_2O_3 ...	6·50	7·82	8·18	7·68	7·90	5·38	6·34
Fe_2O_3 ...	7·23	5·11	4·61	5·38	4·88	4·03	4·60
FeO ...	5·00	5·23	4·98	4·77	5·23	6·47	6·00
MgO ...	14·08	14·76	17·66	15·46	17·58	24·84	20·06
CaO ...	16·79	14·28	10·40	9·79	11·03	8·06	10·45
Na_2O ...	1·32	1·27	0·18	0·65	1·05	0·68	1·27
K_2O ...	4·09	5·39	6·98	7·04	4·98	3·46	3·66
H_2O+	2·78	2·29	1·42	1·66	2·36	1·11	2·52
H_2O-	1·15	0·71	0·50	0·97	0·40	0·57	1·08
CO_2 ...	0·09	0·58	trace	0·34	0·14	0·36	trace
TiO_2 ...	3·87	4·09	4·36	4·75	4·29	3·52	4·44
P_2O_5 ...	0·74	0·76	0·61	0·42	0·36	0·29	0·45
Cl ...	0·02	—	—	trace	—	0·01	—
F ...	0·16	0·12	0·13	0·18	0·09	0·10	0·10
S ...	0·35	0·16	0·13	0·09*	0·12	0·04	0·18
V_2O_3 ...	0·03	—	—	0·03	—	0·03	—
Cr_2O_3 ...	0·01	0·07	0·08	0·14	0·09	0·11	0·02
NiO ...	0·19	trace	trace	0·05	0·08	0·13	0·08
MnO ...	0·24	0·25	0·26	0·15	0·27	0·23	0·09
BaO ...	0·25	0·26	0·32	0·34	0·21	0·27	0·22
SrO ...	0·04	0·21	0·18	0·18	0·22	0·02	0·16
	100·36	100·41	100·04	100·07	100·56	100·18	100·34
Less O	0·24	0·11	0·10	0·07	0·09	0·05	0·11
	100·12	100·30	99·94	100·00	100·47	100·13	100·23

*SO_3

A. Katungite, C.4407. Near end of western lava-flow of Katunga, 12 miles SSE. main Bunyaruguru field. Analyst, A. W. Groves (Holmes, 1936, p. 414, and 1937, p Total includes ZrO_2 none, CuO 0·06, Li_2O none.

B. Melilite-mafurite, C.6107. Ejected block from Lake Kamunzukwa crater. A W. H. Herdsman.

C. Mafurite, C.6073. Ejected block from the tuffs above the lava-sheet of Mafuru. A W. H. Herdsman.

D. Biotite-mafurite, C.4043. Ejected block from Nyungu crater. Analyst, H. F. Ha

E. Leucite-mafurite, C.4007. Lava-dome of Chamengo crater. Analyst, W. H. Herd

F. Olivine-rich ugandite, C.3052. Volcanic bomb from Old Kichwamba rest-camp, ing Kachuba crater. Analyst, H. F. Harwood (Holmes and Harwood, 1932, p Total includes ZrO_2 none, Li_2O trace.

G. Melilite-ugandite, C.3989. Driblet, near SE. limit of main lava-flow, Kazimiro, 2½ SW. of Lake Mafuru. Analyst, W. H. Herdsman.

H. Katungite, C.3509. Volcanic bomb from tuffs of upper part of NE. wall of Chama crater, 3½ miles N. of Kasidia crater. Analyst, W. H. Herdsman. The 'norm' is calc to be comparable with the others, but the rock itself contains pyroxene only as xeno

In fig. 2 the rocks are plotted in a triangular field of a system of co-ordinates presenting the distribution of K_2O and CaO, these being the two constituents at give the maximum separation of the types. The three main types—katungite ith high CaO), mafurite (with high K_2O), and ugandite—occupy the corner lds of the triangle. From the katungite corner SiO_2 rises towards mafurite d ugandite as CaO falls. The essential difference between mafurite and ugandite the higher K_2O of the former.

TABLE IV. Normative compositions.

	A.	B.	C.	D.	E.	F.	G.	H.
iophilite ...	—	18·06	18·06	11·38	13·16	—	—	—
ucite ...	18·94	—	7·42	16·93	4·93	16·01	16·98	16·40
pheline ...	5·80	5·54	0·82	0·23	4·80	3·10	5·82	6·93
orthite ...	—	—	0·89	—	2·14	1·50	0·78	9·18
mite ...	0·28	0·46	—	3·97	—	—	—	—
psside ...	14·96	36·37	34·23	30·49	37·31	24·49	22·88	10·77
$_2SiO_4$ ...	16·18	4·21	—	—	—	0·89	5·79	10·74
rsterite ...	19·71	13·92	19·70	17·07	18·55	37·82	27·57	17·66
gnetite ...	10·37	7·18	6·69	5·81	7·09	5·83	6·66	9·67
nenite ...	3·96	6·42	6·53	6·56	6·79	6·67	8·22	5·96
romite ...	—	0·11	0·11	0·20	0·13	0·16	0·02	—
rite ...	0·65	0·30	0·24	—	0·22	0·07	0·34	—
rovskite ...	3·03	1·21	1·58	2·20	1·22	—	0·18	5·01
atite ...	1·75	1·82	1·45	1·01	0·84	0·67	1·08	2·66
norite ...	0·22	0·11	0·16	0·29	0·12	0·20	0·12	—
cite ...	0·21	1·32	—	0·77	0·32	0·82	—	0·96
ater ...	3·93	3·00	1·92	2·63	2·76	1·68	3·60	4·08
	99·99	100·03	99·80	99·70*	100·38	99·91	100·04	100·02

* Total includes Na_2SO_4 = 0·16.

The low summations compared with those of table III are due to reckoning BaO and SrO CaO.

It will be seen that mafurite and biotite-mafurite are closely similar and can refore be regarded as heteromorphs. The Chamengo leucite-mafurite has less O but more Na_2O and occupies a position in fig. 2 where there should be ample portunity for heteromorphism, since the combinations leucite-melilite and lsilite-augite overlap chemically. Inspection of table IV shows that the 'norms' B, C, D, and E might have been calculated with leucite instead of kaliophilite l Ca_2SiO_4 and Mg_2SiO_4 instead of part of the diopside. The corresponding ilite-rocks, if they existed, would be leucite-rich olivine-melilitites or highly tassic alnöites. So far, however, no such rocks are known, here or elsewhere. e nearest examples all differ in containing more Na_2O and less K_2O. Considera- of all the analyses available indicates that in the field under review kalsilite pears when the ratio of K_2O to total alkalis is high (0·8 or more), and that stallization of melilite and/or leucite is favoured when there is less K_2O and re Na_2O. The relatively high Na_2O of melilite-mafurite, leucite-mafurite, and ilite-ugandite illustrate this point. It will be recalled that Bowen 22', p. 17) has demonstrated that melilite tends to form by reaction from i-crystallized diopside in a considerable part of the nepheline-diopside system. As a whole, the mafurite series shares the characteristic petrochemical

peculiarities of the Toro-Ankole province, namely: relatively high Ti, P, F, B and Sr, with notable but fluctuating amounts of S or SO_3, Ni, and Cr (cf. Holmes and Harwood, 1932, p. 420; Holmes, 1937, p. 207).

The only potassic rocks from other regions which are even approximately of analogous composition are venanzite (leucite-rich katungite) from the Roman province (Rodolico, 1937, p. 44), and madupite (diopside-phlogopite-leucitic glass) from the Leucite Hills of Wyoming (Cross, 1897, pp. 130, 134). These have higher SiO_2, Al_2O_3, CaO, and K_2O, and lower iron oxides, MgO and TiO. Soda-rich analogues of the mafurite series have not been traced. The nearest comparable types are rocks described under such names as ankaratrite, melilite-ankaratrite, and tannbuschite (Johannsen, 1938, p. 364). All of these have much more Al_2O_3 than mafurite and are conspicuously augite-rich rocks. True analogues would be olivine-rich mela-nephelinites.

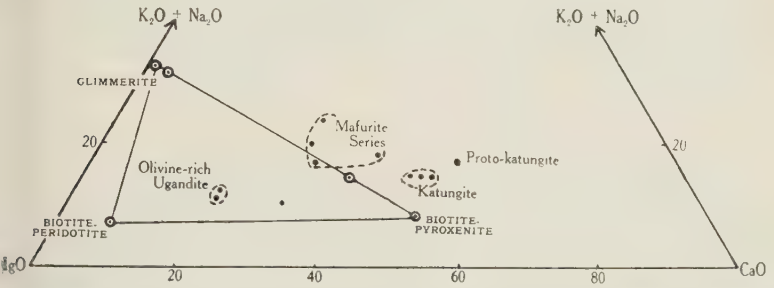
Sequence.—From the limited evidence available in 1932 it was thought that the general sequence of the volcanic types in the Toro-Ankole fields was from katungite and related melilitic rocks, through transitional varieties, to ugandite and related leucitic rocks. Though it remains true that this is locally a common partial sequence, it is now clear that it is by no means the whole story. In Bunyaruguru the 'older' tuffs provide ample evidence that some examples of ugandite or olivine-rich ugandite are older than some occurrences of katungite, and that these types alternated, probably several times. The tuffs of Lugazi Hill, to the east of Nyungu crater, contain accessory lapilli of proto-katungite, katungite, and ugandite, as well as essential—and therefore later—lapilli of katungite. These tuffs are older than those of the Nyungu and neighbouring craters, all of which contain still later essential lapilli of katungite. Mafurite has not been detected in the 'older' tuffs.

At Mafuru, mafurite is followed by katungite. At Chamengo, leucite-mafurite and kalsilite-ugandite (associated in one specimen with olivine-leucitite) are followed by katungite. At Kamunzukwa, melilite-mafurite is followed by katungite. In the Nyungu–Kakunyu–Kachuba group of craters bombs of olivine-rich ugandite appear to be the latest products. At Kakunyu, for example, one of these bombs contains a core of katungite tuff. No detailed succession can yet be given, but it can at least be stated that the mafurite occurrences are both preceded and followed by proto-katungite, katungite, and members of the ugandite series.

Associated Xenoliths.—It is clear that the three leading types—katungite, mafurite, and ugandite—are closely related in space, time, and composition. All three types, and also the transitional varieties, contain relics of more or less resorbed xenoliths and xenocrysts belonging to the biotite-pyroxenite–glimmerite–biotite-peridotite suite. The petrological evidence, a little of which is recorded in this and earlier communications, indicates that the volcanic rocks are rheomorphic products due to the action of highly ultrabasic magmatic material or rock material which is represented by the xenoliths. Fig. 3 is a triangular diagram which helps to bring out the chemical relationships between the lavas and the xenolithic rocks.

Biotite-pyroxenite is found to be the predominant associate of katungite (Holmes, 1937, p. 217), and the magmatic ancestry in this case can be traced back as far as proto-katungite. Fig. 3 shows that these three types fall close

her. Olivine-rich ugandite, however, falls nearer to biotite-peridotite, and ination of numerous specimens of olivine-rich ugandite shows that the iths consist largely of olivine, olivine aggregates, and bits of biotite-peridotite. e case of mafurite, biotite-pyroxenite, glimmerite, and biotite-peridotite all contributed, but the evidence so far collected hardly justifies a statement order of relative abundance, except for biotite-mafurite, where xenolithic e is invariably important. It is obvious from fig. 3, however, that glimmerite ot have contributed the whole of the excess potash-content of biotite-rite; moreover, had it done so, it would have added much more Al_2O_3 than ent in biotite-mafurite.



. 3. Triangular diagram (in terms of MgO, CaO, and alkalis) showing the relationships volcanic types of Bunyaruguru to the associated cognate plutonic types.
he mafurite series the dot nearest to the katungite field represents melilite-mafurite, nat nearest to olivine-rich ugandite represents leucite-mafurite. Melilite-ugandite is ented by the dot between katungite and olivine-rich ugandite.

itic and granitic xenoliths also contribute to at least some of the lavas. is growing evidence, as the collections are examined, that the development icite instead of kalsilite, and of augite instead of melilite, is due to the poration of such sialic material, especially in the ugandite series. It may ted here, in passing, that no signs of limestone assimilation have been ted, and that the distribution of what little limestone or dolomite there is area is entirely independent of that of the volcanic rocks, both as a whole s regards the individual types.

ere remains for consideration the nature and composition of the magmas gmatic emanations responsible for the volcanic rocks under review. An pt has already been made to attack this problem in the case of katungite nes, 1937, p. 214) and, as indicated above, the discovery of proto-katungite rried this enterprise one stage further back. It is hoped in a later paper to nstrate that similar magmatic material, acting on a different suite of nic rocks, may have been responsible for the genesis of members of the li e series. In the case of the mafurite series the composition of the magmatic ri l must have been different; but, beyond leading to the almost obvious that it was much richer in K_2O and very poor in Na_2O, the attempts made e tangle the composition have so far led to no convincing conclusions. kalsilite-katungite may provide a clue, but until sufficient material of e can be separated for complete analysis, the problem must remain ved.

9. Acknowledgements.

I am deeply grateful to the Officers of the Geological Survey of Ugand
providing the suite of rocks investigated, and in particular to Mr. A. D. Co
who collected the specimens and freely placed at my disposal the results o
field work. Grateful acknowledgement is also made to Dr. H. F. Harwoo
contributing the analysis of biotite-mafurite and for determining the alka
a sample of kalsilite-pegmatitoid; to Mr. F. A. Bannister and Dr. M. H. He
undertaking the X-ray, optical and micro-chemical investigation of the
mineral, kalsilite; and to the Research Fund Committee of the Council o
Durham Colleges for a grant out of which the cost of the other new ana
has been defrayed. Thanks are also due to Mr. G. W. O'Neill for his conti
assistance in the preparation of thin sections and photomicrographs.

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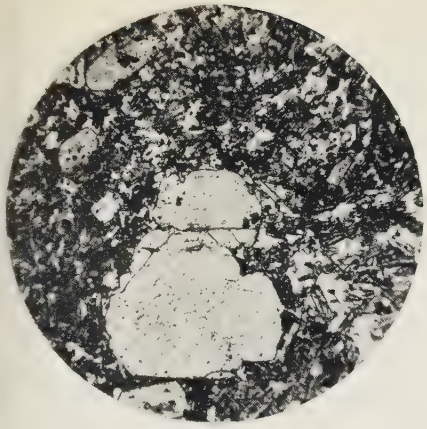

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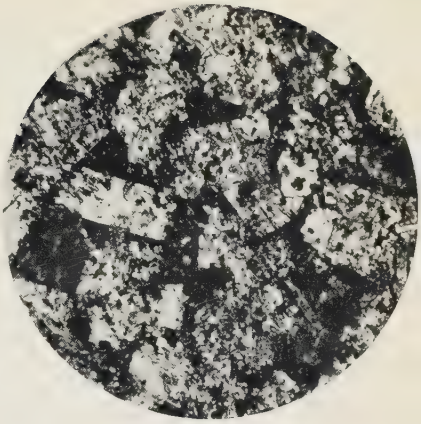

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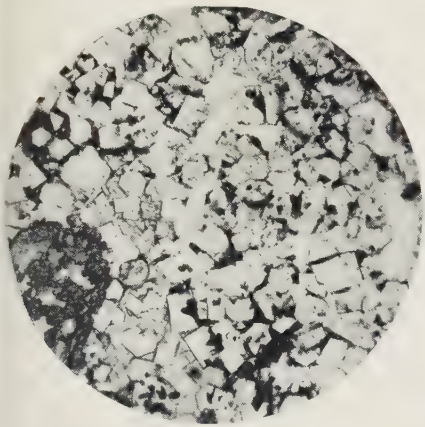

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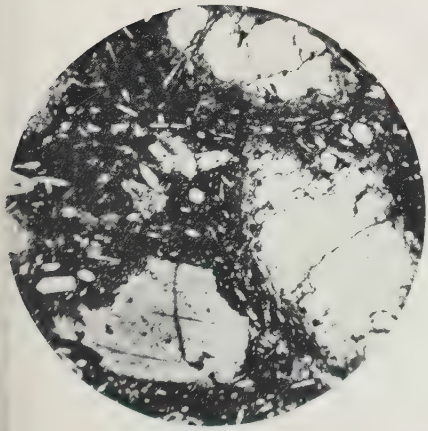

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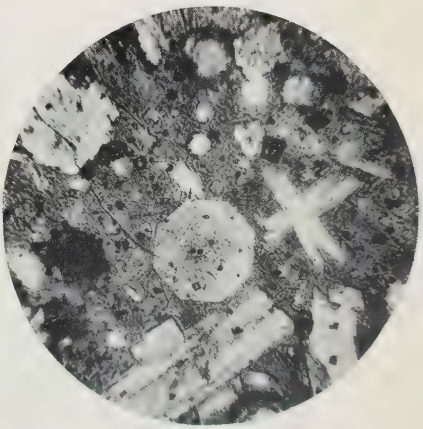


6

ARTHUR HOLMES: MAFURITE SERIES.

11. Description of Plate VI.

1. Mafurite, C.6073. Ejected block from tuffs above lava-sheet, Mafuru dry crater. ...rophenocrysts of olivine and diopsidic augite occur in a groundmass containing micro... of diopsidic augite and grains of perovskite and black ore in a mesostasis consisting ...inly of kalsilite. ×20.

2. Groundmass of coarse variety of mafurite, C.6075, occurring as lapilli in tuffs above ...-sheet, Mafuru dry crater. The field illustrates the occurrence of poikilitic kalsilite as ...hedral and euhedral crystals. ×36.

3. Pegmatitoid in mafurite, C.6075. The field shows an area rich in euhedral kalsilite ...h interstitial calcite; a marginal group of crystals of diopsidic augite is seen on the left. ...6.

4. Pegmatitoid in mafurite, C.6073. Diopsidic augite occurs in a background of poikilitic ...silite associated with a little biotite. ×36.

5. Biotite-mafurite, C.4078. Ejected block from NW. wall of Mafuru lake-crater. ...rophenocrysts of olivine, rimmed with biotite, and a xenocryst of biotite are embedded ...biotite-rich kalsilitic groundmass, the laths and microliths of which are diopsidic augite. ...8.

6. Kalsilite-katungite, C.5962, occurring as lapilli in tuffs, north side of Kabirenge valley, ...out 2000 feet west of Changabe crater. Prismatic and basal sections of melilite, prisms ...kalsilite with 'forked' and 'frayed' terminations (including a cross-like intergrowth, ...sibly a twin), irregular crystals of olivine (NW. and SE. of field), and grains of ...ovskite are embedded in a matrix of glass. ×120.

...micrographs, all in ordinary light, by G. W. O'Neill, University Science Laboratories, ...rham.

Kalsilite, a polymorph of $KAlSiO_4$, from Uganda.

(With Plate VII.)

By F. A. Bannister, M.A.

With chemical analyses by Max H. Hey, M.A., D.Sc.

Mineral Department, British Museum.

[Read January 22, 1942.]

PROFESSOR ARTHUR HOLMES has described in the preceding pap suite of rocks from Mafuru, Uganda. During his study he observed in section a mineral which in optical properties is indistinguishable from nephe He gives chemical evidence, however, for the presumption that a potass aluminosilicate is present in mafurite which would suggest either that nepheline-like mineral is kaliophilite or a polymorphous form of $KAlSiO_4$. K philite is not isomorphous with nepheline, but has similar optical proper and the two minerals could be easily confused in thin section. They may, howe be rapidly distinguished by X-ray methods.[1] Even minute grains insuffic for chemical analysis can be determined with certainty; so it seemed prob that an X-ray study of the nepheline-like mineral from Uganda would additional information and decide whether or no a separation and chen analysis of the mineral should be attempted. Professor Holmes accordi invited me to examine his specimens and rock-sections.

A complete petrographic description of these specimens has already been gi Briefly, they are composed of a dark-coloured, fine-grained matrix enclo abundant and large crystals of magnesium-rich olivine. Some of the h specimens show greenish-yellow patches which Professor Holmes terms 'pegm toid segregations'. In thin section these segregations reveal transparent colou grains of low birefringence rarely more than 0·1 mm. across, abundant pale g diopside crystals up to 0·2 mm. across, and granular calcite. The colou grains are the nepheline-like mineral and they are intergrown with pale br phlogopite and with a nearly isotropic material of lower refractive index. Phl pite also is concentrated in the rim of the 'pegmatitoid segregation'.

The first X-ray photographs of the nepheline-like mineral were take fragments detached from the edge of a thin section of mafurite which had prepared without a cover glass. These showed conclusively that the miner neither nepheline nor kaliophilite. It was therefore desirable to isolate suffi for chemical study. Only one hand-specimen (C.6073) of mafurite was avail with a 'pegmatitoid segregation' large enough to be detached from the ma The segregation was roughly spherical, about 1 cm. in diameter, and deta fragments showed the presence of numerous grains of the mineral to be isol By chiselling and the use of dental tools $\frac{1}{2}$ gram of the segregation was freed matrix. This was powdered coarsely and then treated with bromoform to sep

[1] F. A. Bannister and M. H. Hey, Min. Mag., 1931, vol. 22, p. 569.

diopside which weighed 0·20 g. On diluting the bromoform the specific ity of the remaining grains was found to vary between wide limits owing to r composite nature. They were separated into two approximately equal tions: I, sp. gr. 2·62–2·67; and II, sp. gr. 2·45–2·62. Fraction I contained a calcite which was removed by hand-picking. Microscopic and X-ray nination showed that the remainder of this fraction was composed chiefly e nepheline-like mineral and its micro-chemical analysis is given in table I. rate single crystal grains of the mineral visibly free from inclusions and quite rless yield specific gravity values 2·59±0·03.

Table I. Micro-chemical analysis of kalsilite.

Fraction of sp. gr. 2·62–2·67.			Atomic contents per 8 oxygen atoms.			
SiO_2*	...	39·6	Si	...	2·13	
Al_2O_3	...	21·3	Al	...	1·35	1·59
Fe_2O_3	...	5·9	Fe	...	0·24	
MgO	...	3·7	Mg	...	0·30	
CaO	...	5·0	Ca	...	0·29	
K_2O	...	20·1	K	...	1·38	1·55
Na_2O	...	1·6	Na	...	0·17	
		97·2				

·5 mg. of the fraction were used for analysis and yielded SiO_2 39·2 %. 12 mg. were used e alkali determination; this gave a second value for SiO_2 40·5 %. The figure 39·6 is the ted mean of 39·2 and 40·5.

·08 mg. of picked grains of kalsilite was ignited at 800° C. for one hour. The ignition loss t than 1 %.

e composition of fraction I is approximately $KAlSiO_4$; the iron, calcium, particularly magnesium figures obtained may be due partly to inclusions logopite and perhaps diopside. Many grains of the mineral possess a yellow which is due to internal films. These grains turn brown on heating, suggesting sions of an iron mineral. Not all the iron content given by analysis is nted for by inclusions or admixture with other minerals, however, for colourless grains are readily attacked by dilute hydrochloric acid giving a inous liquid coloured yellow by the presence of ferric chloride.

tical examination of grains of the mineral revealed some oriented to give rp, nearly uniaxial negative picture. The refractive indices determined by Becke line method are ω 1·542, ϵ 1·537±0·002. No grains with hexagonal e have been found and no trace of a cleavage was discovered. Grains for -crystal X-ray photographs were set up approximately by optical methods hen finally adjusted along zone axes by Laue and oscillation photographs. neral is truly hexagonal and possesses unit-cell dimensions a 5·17, c 8·67 A. ing the unit-cell content is $2KAlSiO_4$, the specific gravity is calculated to . From the composition given by analysis the specific gravity is calculated 2·57, in fair agreement with the observed value 2·59.

dexing oscillation photographs of the mineral about the a- and c-axes no tic halvings were discovered for any spectra save those from the basal . All odd orders of $c(0001)$ are missing. The space-group is thus determined ocally as $D_6^6 = C6_32$ which possesses no planes of symmetry. Since an photograph adds a centre of symmetry to the diffraction pattern, which

in this instance is not present in the lattice, planes of symmetry are ad
perpendicular to the two-fold axes. Hence a Laue photograph along the *c*-a
of the mineral (pl. VII, fig. 1) shows not only hexagonal symmetry but also li
of symmetry parallel to $(10\bar{1}0)$ and $(11\bar{2}0)$.

The unit-cell dimensions of nepheline vary between the limits *a* 9·93–10·05 Å
c 8·33–8·43 Å., so that structurally the new mineral is more closely related
nepheline than to kaliophilite with dimensions *a* 26·7–27·0 and *c* 8·49–8·51
Kaliophilite has a complicated structure which may be viewed as built up fr
nepheline-like cells having the dimensions $a\ 27{\cdot}0/3\times 2/\sqrt{3} = 10{\cdot}4$ Å. and *c* 8·5
The slightly larger dimensions for the nepheline-like cell are of the order to
expected in the replacement of sodium by potassium. The interesting point n
reached is that the new mineral, which may undoubtedly be regarded a
polymorphous form of $KAlSiO_4$, is not isomorphous with nepheline and yet
a-axes are related more simply (i.e. by a factor of two, $2\times 5{\cdot}17 = 10{\cdot}34$ Å.) th
are the *a*-axes of the new mineral and kaliophilite. An analogy is the break
the plagioclase series somewhere near the composition of labradorite where
c-axis is doubled. Plagioclases richer in soda are isomorphous with each ot
(*c* 7·17 Å.) and plagioclases above the break containing less soda (*c* 14·16
are also isomorphous with each other, but the series albite to anorthite i
broken one.[1] The difference between the new mineral and nepheline is mark
not only by a doubling of the cell-side *a*, but also by change of space-group.
is not possible without X-ray examination of the hexagonal form of artifi
$KAlSiO_4$ which various workers have made, to decide whether G. Friedel[2] a
N. L. Bowen[3] are correct in contending that it is truly isomorphous with nepheli

Dr. M. H. Hey has succeeded in preparing the orthorhombic form[4] of KAlS
twinned like aragonite, but so far has not synthesized the new mineral nor
a potassium-nepheline. It is probable that a polymorph of $KAlSiO_4$ tr
isomorphous with nepheline does not exist and that the hexagonal form
$KAlSiO_4$ reported by Friedel, Bowen, and Trömel[5] is closely related to, if
identical with, the new mineral. Bowen states that both the hexagonal a
orthorhombic forms of artificial $KAlSiO_4$ can be obtained at low temperatu
500 600° C., but that the hexagonal form inverts to the orthorhombic form
the neighbourhood of 1540°; hence the latter is the stable form at high tempe
tures. An artificial preparation of kaliophilite has also been prepared at 2
211° C. which gives the same X-ray powder pattern as kaliophilite from Mo
Somma.[6] In view of the lack of accurate thermal data on the three kn
polymorphous forms of $KAlSiO_4$ it would be unwise at the present time to

[1] W. H. Taylor, J. A. Darbyshire, and H. Strunz. Zeits. Krist., 1934, vol. 87, p.
[M.A. **6**–177.] S. H. Chao and W. H. Taylor, Proc. Roy. Soc. London, Ser. A, 1940, vol.
p. 76. [M.A. **8**–13.]

[2] G. Friedel, Bull. Soc. Franç. Min., 1912, vol. 35, p. 471.

[3] N. L. Bowen, Amer. Journ. Sci., 1917, ser. 4, vol. 43, p. 115. [M.A. **1**–167.]

[4] A. Duboin, Compt. Rend. Acad. Sci. Paris, 1892, vol. 115, p. 56. Bull. Soc. Franç. M
1892, vol. 15, p. 191.

[5] G. Trömel, Veröffentlichungen aus dem Kaiser Wilhelm-Institut für Silikatforschun
Berlin-Dahlem, 1930, vol. 3, p. 103. W. Eitel and G. Troemel, Fort. Min. Krist. Petr., 1
vol. 14, p. 28. [M.A. **6**–60.]

[6] S. J. Thugutt, Arch. Min. Tow. Nauk. Warszaw. (Arch. Min. Soc. Sci. Varsovie), 1
vol. 13, p. 112. [M.A. **7**-146.]

α, β, γ nomenclature, although Trömel and Winchell[1] have already called orthorhombic form α-$KAlSiO_4$. There is no evidence that there is an analogy the α–β transition of quartz which takes place reversibly at a definite perature and involves a distortion of a silicon-oxygen lattice with relatively l changes in unit-cell dimensions. The transition from the highly complex philite with a large unit cell to the new mineral with a much smaller unit nd more simple crystal-structure may not necessarily be effected without ng through an intermediate phase. Naming the new mineral parakalio- te would also be open to the same objection. Parakalinepheline correctly eys the sense of a simple crystallographic relationship to nepheline, but such me is unduly cumbrous. In the circumstances, it is proposed to name the mineral kalsilite after its chemical composition $KAlSiO_4$.

	a.	*b*.	*c*.	ω.	ε.	Sp. gr.
lite	5·17	8·96	8·67Å.	1·542	1·537	2·59
philite	27·0	46·8	8·51	1·530	1·526	2·606
orhombic $KAlSiO_4$	9·00	15·68	8·53	γ1·536	α1·528	2·60

oove are tabulated the known forms of $KAlSiO_4$, together with their X-ray optical data. A more detailed description of further X-ray data on the orhombic form and on yet another polymorph of $KAlSiO_4$ of unknown metry, recently prepared as a powder by Dr. Hey, must await X-ray examina- of the hexagonal form described by Friedel and Bowen. Since the new ral possesses a smaller unit cell than any other member of the nepheline y, a knowledge of its crystal-structure will assist in working out the more plex crystal-structures of nepheline, kaliophilite, and the orthorhombic form $KAlSiO_4$.

wder photographs of kalsilite, kaliophilite, and nepheline are reproduced VII, figs. 2, 3, and 4) to show how readily the three minerals may be dis- uished. The photograph of kalsilite has been indexed and the spacings and sities of the lines are tabulated in table II. These photographs were taken iron radiation to obtain greater resolution than is possible with a copper t. Yet the kaliophilite pattern contains a large number of weak lines very to each other and is in contrast to the much less line-rich pattern of kalsilite.

would obviously be an advantage to petrographers not equipped with X-ray ratus to distinguish between kalsilite and nepheline in thin section. This be done successfully with a straightforward chemical test.[2] A drop of N HCl ced on the uncovered thin section or polished rock surface, and after ½ minute a of strong sodium cobaltinitrite solution is added; after a further 1–2 minutes urface is washed gently. Kalsilite, but not nepheline, gives a yellow stain ific for the presence of potassium.

will be recalled that the chemical composition of the new mineral kalsilite btained from the heavier of two fractions from which the diopside had ly been removed. Fraction II contained grains varying in specific gravity 2·45 to 2·62 and most of them were composite. Many indeed were kalsilite

1. N. Winchell. The microscopic characters of artificial inorganic solid substances or di minerals. 2nd edit., New York, 1931, p. 308. [M.A. 5–2.]

2. Gabriel and E. P. Cox, Amer. Min., 1929, vol. 14, p. 290. [M.A. 4–219.] M. L. Keith, Min., 1939, vol. 24, p. 561. [M.A. 8–17.]

grains, but they were generally attached to, or sometimes surrounded by transparent, colourless, nearly isotropic material of refractive index 1·500. T sections of the 'pegmatitoid segregation' also reveal this interstitial mater which at first was thought to be glass. Fraction II was more finely powdered a eventually separated into two components by centrifuging in a mixture bromoform and benzene with sp. gr. 2·45. The heavier component yielded powder photograph of kalsilite, but the minute amount of mineral sp. gr. < 2 yielded a powder pattern at first attributed to phillipsite. This pattern agr exactly with extra lines and spots found on some of the preliminary powder a particle photographs of the 'pegmatitoid segregation' before crushing and tre ment with heavy liquids. So little of this lighter mineral was separated that specific gravity could not be determined with accuracy; its probable value 2·35 ±0·05. Certain differences in optical properties and the powder patterns the mineral and phillipsite suggested further tests. Dr. Hey found that 0·738 n of fraction II on ignition at 800° C. lost $5 \pm \frac{1}{2}$ %. After ignition these gra showed adherent milky material which disintegrated readily.

Table II. X-ray powder data for kalsilite.

2r. cm.	Intensity.	Spacing: Observed. Å.	Spacing: Calculated. Å.	Index.
2·71	m	4·35	4·335	(0002)
3·00	s	3·97	3·979	$(10\bar{1}1)$
3·49	m	3·12	3·115	$(10\bar{1}2)\beta$
3·85	s	3·11	3·115	$(10\bar{1}2)$
4·20	w	2·572	2·585	$(11\bar{2}0)\beta$
4·65	s	2·590	2·585	$(11\bar{2}0)$
4·86	m	2·470	2·477	$(11\bar{2}1)$
4·95	m	2·428	2·428	$(10\bar{1}3)$
5·45	w	2·218	2·220	$(11\bar{2}2)$
5·60	m	2·163	2·168	(0004)
			2·168	$(20\bar{2}1)$
6·15	w	1·984	1·989	$(20\bar{2}2)$
6·25	w	1·955	1·951	$(10\bar{1}4)$
6·36	w	1·926	1·927	$(11\bar{2}3)$
7·00	w	1·770	1·770	$(20\bar{2}3)$
7·51	m	1·660	1·661	$(11\bar{2}4)$
			1·661	$(21\bar{3}1)$
7·75	m	1·620	1·618	$(10\bar{1}5)$
7·98	m	1·576	1·576	$(21\bar{3}2)$
8·10	vw	1·556	1·557	$(20\bar{2}4)$
8·51	m	1·490	1·492	$(30\bar{3}0)$
8·76	w	1·460	1·460	$(21\bar{3}3)$
9·43	w	1·375	1·375	$(10\bar{1}6)$
9·79	w	1·335	1·334	$(21\bar{3}4)$
10·19	w	1·294	1·293	$(22\bar{4}0)$
10·52	m	1·264	1·261	$(11\bar{2}6)$
10·91	m	1·231	1·229	$(31\bar{4}1)$
			1·229	$(30\bar{3}4)$
11·15	m	1·212	1·212	$(20\bar{2}6)$
			1·214	$(21\bar{3}5)$
11·40	m	1·194	1·193	$(31\bar{4}2)$
12·20	w	1·141	1·142	$(31\bar{4}3)$
12·75	vw	1·111	1·110	$(40\bar{4}1)$
			1·110	$(22\bar{4}4)$
13·29	w	1·085	1·084	$(20\bar{2}7)$
			1·083	$(40\bar{4}2)$
13·44	vw	1·078	1·077	$(31\bar{4}4)$
14·00	w	1·055	1·053	$(10\bar{1}8)$
14·28	w	1·045	1·043	$(40\bar{4}3)$
14·55	w	1·036	1·036	$(22\bar{4}5)$
15·42	m	1·011	1·009	$(31\bar{4}5)$
15·85	m	1·000	1·000	$(32\bar{5}2)$
			1·000	$(11\bar{2}8)$

This and the powder photographs of nepheline and kaliophilite reproduced in pl. VII w taken with unfiltered iron radiation λ 1·934 Å. in a cylindrical camera, 6·04 cm. diameter.

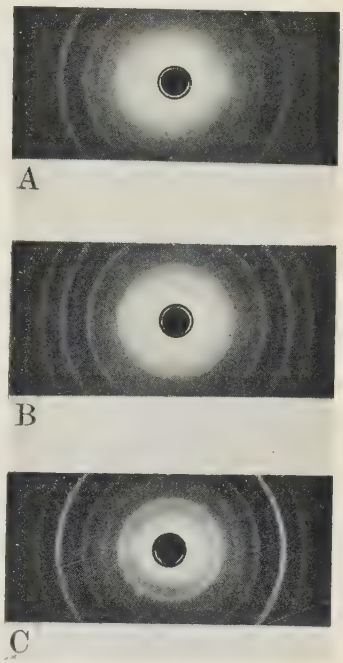
Thus far the weakly birefringent mineral interstitial to kalsilite would appe to be a zeolite, and a member of the phillipsite family. It is distinguished fro phillipsite by lower birefringence, higher specific gravity, and easily detect differences in the spacings and intensities of the lines on powder photograp (text-fig. 1). A comparison with a powder photograph of another well-know

mber of the phillipsite family, harmotome, reveals similarities, especially in lines of high spacing at the centres of the photographs. The spacings and nsities of the powder lines tabulated in table III, however, show that the neral under discussion is neither phillipsite nor harmotome. A positive test barium was obtained by Dr. Hey on a small sample of fraction II which ether with the X-ray evidence points to barium content of the zeolitic mineral.

have not, however, excluded the possi- ty of kalsilite itself containing barium. hough the zeolite associated with kalsilite undoubtedly a member of the phillipsite nily a satisfactory identification with a own mineral has not been achieved. There a possibility that the mineral is identical h wellsite,[1] a member of the phillipsite nily containing 5 % BaO with sp. gr. 2·278–36, but no specimens were available for nparison.

t may be significant that the *c* dimensions he unit cells of harmotome[2] and phillipsite[3] 8·60 and 8·62 Å. respectively, both fairly se to the *c* dimension of kalsilite 8·67 Å. e *c* dimension of the undetermined zeolite ch rims many of the kalsilite grains is likely be sufficiently close to that of kalsilite to gest parallel growth. This idea can be tested re rigorously when the crystal-structure of silite has been worked out.

hin sections of the 'pegmatitoid segrega- ' show calcite filling cracks and flaws in kalsilite-diopside matrix. The calcite some- es encloses fan-shaped crystal groups remi- ent of stilbite and it was possible by olving some of the calcite grains picked n fraction I before analysis, in dilute HCl, btain small particles of a mineral with low fringence and refractive index about 1·48. dles of another mineral, possibly zeolitic, e also obtained in this way, but were too ll for identification. It was possible, however, to obtain an X-ray photo- h of a few particles of the chief mineral enclosed in the calcite. This ed to be identical with the pattern of the undetermined zeolite with refractive x 1·500 associated with kalsilite. It is not unlikely that a member of the ipsite family might vary considerably in chemical composition and in ctive index, but chemical work on the minute amounts just sufficient for and optical data is out of the question.



TEXT-FIG. 1. Powder photographs of zeolite (A) associated with kalsilite, harmotome (B), and phillipsite (C), reproduced from films taken with unfiltered copper radiation, λ 1·539 Å., in the same cylindrical camera, diameter 6·04 cm., to show the lines of longest spacing nearest the centre. Actual size.

[1] H. Pratt and H. W. Foote. Amer. Journ. Sci., 1897, ser. 4, vol. 3, p. 443.
[2] Sekanina and J. Wyart. Bull. Soc. Franç. Min., 1937, vol. 60, p. 139. [M.A. 7-346.]
[3] Wyart and P. Chatelain. Bull. Soc. Franç. Min., 1938, vol. 61, p. 121. [M.A. 7-347.]

The X-ray, chemical, and optical studies have led to a more exact knowledg of the mineral composition of the 'pegmatitoid segregation', which contain approximately 50 % by weight of kalsilite, 40 % of diopside, and not mo than 10 % of calcite, zeolite, biotite, &c. By centrifuging powdered mafurit surrounding the 'pegmatitoid segregation' a minute quantity of kalsilite wa obtained which gave a powder photograph free from additional lines. It unlikely that the separation of kalsilite from the fine-grained matrix was complet however, and no quantitative estimate of the percentage of the new mineral i samples of mafurite free from segregations has been attempted.

TABLE III. Spacings in Ångström units and the estimated intensities of the principal lines X-ray powder photographs of the zeolite associated with kalsilite and of harmotome an phillipsite.

Zeolite (text-fig. 1A).		Harmotome (text-fig. 1B).		Phillipsite (text-fig. 1C).		Zeolite (text-fig. 1A).		Harmotome (text-fig. 1B).		Phillipsite (text-fig. 1C).	
8·18	s	8·11	s	7·64	s	1·97	vw	1·95	m	2·16	vw
7·16	s	7·16	s	6·91	s	1·78	w	1·91	vw	2·07	vw
6·43	m	6·25	s	6·34	vw	1·72	w	1·84	w	1·97	w
4·96	vw	4·96	m	5·24	w	1·65	vw	1·80	w	1·91	vw
4·07	m	4·07	s	4·91	w	1·55	vw	1·74	w	1·84	vw
3·51	w	3·50	m	4·56	vw	1·49	vw	1·72	ms	1·78	w
3·18	s	3·18	s	4·25	m	1·37	vw	1·68	w	1·72	w
2·95	w	2·93	w	4·07	m	1·33	vw	1·54	m	1·67*	vw
2·70	m.	2·69	s	3·54	w	1·27	vw	1·48	m	1·61	vw
2·55	w	2·52	m	3·18	s			1·37	w	1·55	vw
2·34	vw	2·34*	m	2·94	w			1·33	w	1·49	vw
2·25	vw	2·25	w	2·71	m			1·26	w	1·38	w
2·16	vw	2·16	m	2·52	w			1·17	vw	1·34	w
2·06	vw	2·03*	w	2·40*	w					1·28*	w

* Unresolved doublets.

EXPLANATION OF PLATE VII.

The Laue photograph was taken with unfiltered copper radiation, λ 1·539 Å., the crysta film distance being 3·5 cm. Actual size.

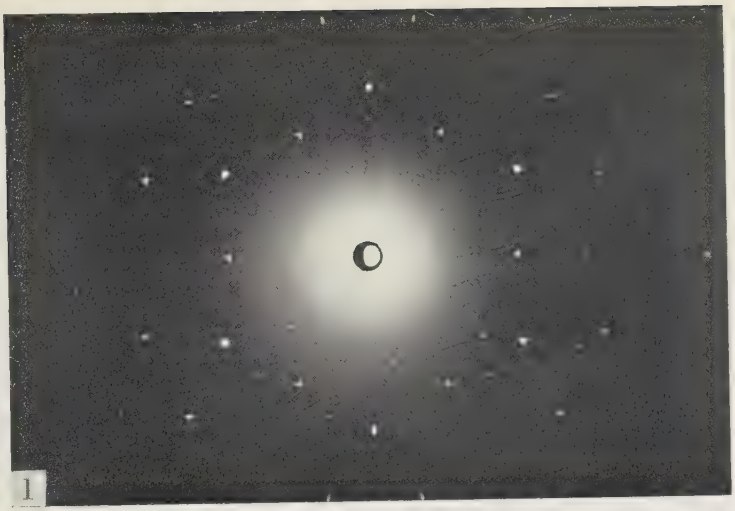
The powder photographs were taken with unfiltered iron radiation, λ 1·934 Å., in the san cylindrical camera, 6·04 cm. diameter. All actual size.

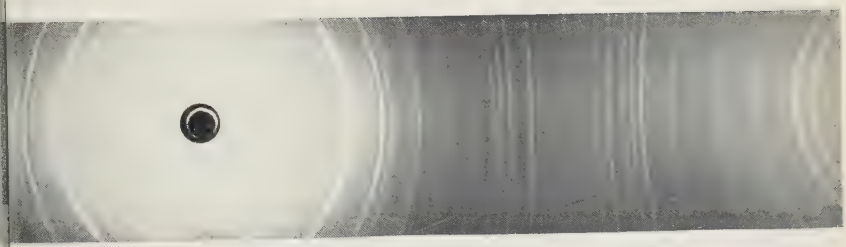
FIG. 1. Laue photograph along the c-axis of a kalsilite grain from a 'pegmatitoid segregatio in mafurite, Mafuru, Uganda.

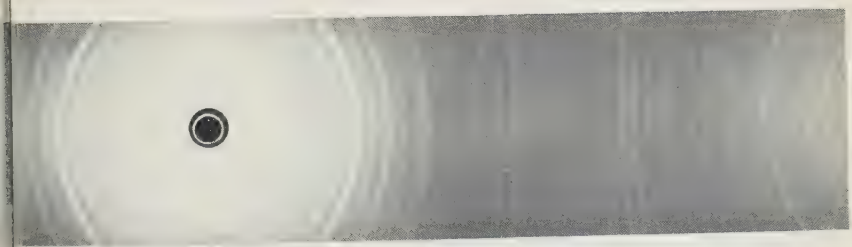
FIG. 2. Powder photograph of kalsilite from fraction I, micro-chemical analysis by M. H. He table I.

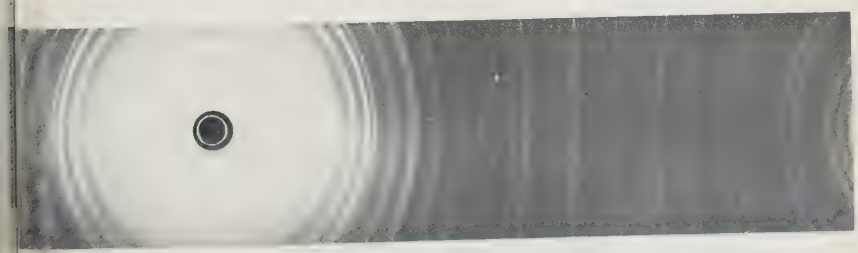
FIG. 3. Powder photograph of kaliophilite from an ejected biotite-augite block, Mon Somma, Mt. Vesuvius, Italy. B.M. 68764.

FIG. 4. Powder photograph of nepheline from leucitite, Capo di Bove, Rome, Italy. B. 1926,1538.









F. A. Bannister: X-ray Photographs of Kalsilite, etc.

Merwinite as an artificial mineral.[1]

(With Plate VIII.)

By James Phemister, M.A., D.Sc.

Petrographer, Geological Survey and Museum, London.

With an appendix by R. W. Nurse, M.Sc.

Building Research Station, Watford, Herts.

and X-ray measurements by F. A. Bannister, M.A.

Deputy Keeper, Mineral Department, British Museum.

[Read January 22, 1942.]

N the investigation of the system CaO–MgO SiO_2 by Ferguson and Merwin[2] the orthosilicate $3CaO.MgO.2SiO_2$ was not observed, and the existence of s compound was first proved in 1921 by Larsen and Foshag[3] who detected it a contact-altered limestone at Crestmore, California, and gave to it the name rwinite. Since then this compound has been found in contact-altered limestones Scawt Hill, Antrim,[4] near Neihart in the Little Belt Mts. of Montana,[5] and Velardeña, Mexico.[6] The history of the recognition of merwinite as an artificial neral is less easy to trace, but it seems that research workers on refractory cks were the first to recognize its existence. Thus U.S.A. Patents applied for the years 1934 and 1935 and British Patents applied for on 11.10.1935 and 5.1936 by Non-Metallic Minerals Inc. specify merwinite and periclase as the ential constituents of a refractory brick produced by firing mixtures of omite and serpentine, dolomite and sand, or impure magnesite and dolomite temperatures varying between 2700° and 2900° F. (that is, about 1500–0° C.). The last Patent specifies the addition of mineralizers (oxides of boron, osphorus, or chromium) to obviate deterioration of the merwinite bricks when d in circumstances permitting reaction with lime. The implication of this vice is that merwinite and lime react readily with formation of β-calcium hosilicate and periclase, the tendency of the former to 'fall' or 'dust' with sequent disintegration of the brick being counteracted by the mineralizing nts. No diagnostic properties of merwinite are communicated in these cifications, nor by Dr. Reinhart[7] who gives some details of the occurrence of

[1] Communicated by permission of the Director, Geological Survey and Museum.

[2] J. B. Ferguson and H. E. Merwin, Amer. Journ. Sci., 1919, ser. 4, vol. 48, p. 81. [M.A. 1–321.]

[3] J. S. Larsen and W. F. Foshag, Amer. Min., 1921, vol. 6, p. 143. [M.A. **1**–254.]

[4] F. E. Tilley, Min. Mag., 1929, vol. 22, p. 84.

[5] H. H. Taylor, Amer. Min., 1935, vol. 20, p. 124. [M.A. **6**–125.]

[6] F. E. Tilley, Geol. Mag. 1928, vol. 65, p. 372. [M.A. **4**–84.]

[7] Reinhart, Tonindustrie Zeitung, 1939, vol. 63, p. 29.

merwinite in refractory bricks. Reinhart states that merwinite has alrea begun to form at a temperature of 1375° C., that monticellite is also a constitue of the bricks, and that the calcium orthosilicate : merwinite ratio is controll in firing mixtures of lime, magnesia, and silica by the ratio $CaO : SiO_2$. Betwe the limits $1{\cdot}4 < CaO : SiO_2 < 1{\cdot}8$ the product after firing will contain bo β-$2CaO.SiO_2$ and $3CaO.MgO.2SiO_2$, merwinite being dominant between t limits $1{\cdot}4 < CaO : SiO_2 < 1{\cdot}6$.

In 1936 H. zur Strassen,[1] and later H. Schwiete and Strassen, described t results of experiments undertaken to test the reactions between lime and forsteri and lime and åkermanite. After firing at 1250° C. for two minutes åkermani was completely and forsterite 80 % destroyed. In both cases the final produc were β-$2CaO.SiO_2$ and MgO, but the intermediate compounds, monticellite ar merwinite in the case of the experiment with forsterite, and merwinite in t case of åkermanite, were formed as transient products. The identification of t compounds was done by X-ray methods, and the authors report also as transie products mixed crystals between merwinite and β-$2CaO.SiO_2$ and between mont cellite and β-$2CaO.SiO_2$. Tests were also made on a mixture of pure CaO, Mg and SiO_2 in the proportions appropriate to the reaction $2CaO+2MgO+SiO_2 =$ β-$2CaO.SiO_2+2MgO$, firing being at 1000° C. for periods increasing by half-hou intervals. For the shorter periods of firing 10–15 % of merwinite was found i the product; after $2\frac{1}{2}$ hours some merwinite was still present, but after 18 hou (no observation having been made between these two periods) merwinite ha disappeared.

In 1938 the writer[2] and Belyankin and Korchemkin[3] reported independentl the occurrence of merwinite as an essential constituent in blast-furnace slag Review of the slags in the Tested Roadstone Collection of the Geological Museu shows that seven out of a total of 32 slags contain merwinite, and it is interestin to note that among the seven is the very first slag to arrive in this collectio in the year 1911. Merwinite is therefore a common mineral in British blast furnace slags and indeed is second only to pseudowollastonite as the subordinat essential constituent, melilite being consistently the major constituent. Pseud wollastonite and merwinite have naturally not been observed in the same slag

During a discussion on the constituent minerals of blast-furnace slags th writer drew the attention of Dr. F. M. Lea and his colleagues of the Buildin Research Station to the comparatively frequent presence of merwinite an Dr. Lea agreed to attempt the synthesis of this compound from the pure oxide This was successfully accomplished and Dr. T. W. Parker has kindly supplie the following notes of its preparation:

'The starting materials were calcium carbonate (99·92 % purity), quart (99·82 % purity), and magnesia (99·73 % purity), all in powder form, fine than a B.S. no. 170 sieve, and intimately mixed in the proportions require for $3CaO.MgO.2SiO_2$. Two mixes were made, one of them containing an 0·5 % admixture of B_2O_3. Both were heated in platinum boats in a platinum wire

[1] H. zur Strassen, Zement, 1936, vol. 25, p. 218; H. Schwiete and H. zur Strassen, Zement 1936, vol. 25, pp. 849, 870.

[2] J. Phemister, Summ. Progr. Geol. Surv. Great Britain, 1938, for 1937, p. 87.

[3] D. S. Belyankin and L. I. Korchemkin, Trav. Inst. Pétrogr. Acad. Sci. U.R.S.S., 1938 no. 12, p. 203. [M.A. 7–286.]

round electric muffle furnace for one hour at 1450° C. They were then cooled, re-ground to pass a B.S. no. 170 sieve, re-mixed and re-heated for one hour at 1500° C. The mix containing B_2O_3 gave a homogeneous product by check test under the microscope at the end of this treatment and was therefore considered to be fully reacted. The mix without B_2O_3 required a further hours heating at 1500° C. before the product became homogeneous. In both cases the preparations were taken out of the furnaces at about 1450° C. and quenched by rapid cooling from this temperature to prevent any possibility of inversion or decomposition.'

From the above summary it is clear that up to the present merwinite, $3CaO.MgO.2SiO_2$, is known to have crystallized from a melt only in the case of blast-furnace slags where, in addition to CaO, MgO, and SiO_2, the oxides Al_2O_3 and FeO are also present, respectively in considerable and in minor proportions. The experiments by Strassen suggest that it is unlikely that merwinite can crystallize from a pure CaO–MgO–SiO_2 melt, but it may be recalled that in these experiments the proportion of SiO_2 is exactly that required for combination with CaO to form $2CaO.SiO_2$. While, therefore, there exists at present no direct challenge to the accuracy of the equilibrium diagram prepared by Ferguson and Merwin it is worth remembering that the investigations on which this diagram is based were made before the existence of merwinite was suspected and its properties known, and also that, the optical properties of synthetic merwinite (see table I below) being very close to those of β-$2CaO.SiO_2$, the possibility of solid solution between these two compounds is not to be disregarded.

The fact that merwinite can crystallize from blast-furnace slag is of the first importance from the economic standpoint. In contrast to the calcium orthosilicate, merwinite does not appear to undergo transformation in the solid state. It is well known that the former crystallizes as the α- or β-phase at high temperature and that at 675° C. the β-phase inverts to a γ-phase with great increase in volume. In consequence, slag containing the calcium orthosilicate as an important constituent is liable to disintegrate or 'fall'. Where, therefore, blast-furnace practice is such that an orthosilicate is present in the slag, the latter can be 'stabilized' by the use of a dolomitic, or some proportion of dolomitic, in place of a calcareous flux, and is then available (without fear of 'falling') for use in concrete aggregate and roadstone.

Merwinite in blast-furnace slag.—The slags which carry merwinite always contain melilite as their major constituent as prisms or tables which are usually strongly zoned. The melilite is optically negative gehlenite with birefringence moderate in the core and decreasing towards a peripheral zone, which may be isotropic for all or part of the visible spectrum. In some specimens zoning to optically positive åkermanite is continued beyond the isotropic layer. Merwinite shows a variety of habit. When very abundant it has separated out from the molten slag at as early a stage as the gehlenite with which it sometimes forms a graphic intergrowth (pl. VIII, fig. 1). It may occur also as optically continuous grains and as idiomorphic crystals within gehlenite or as poikilitic plates enclosing melilite, these plates attaining a length of 5 mm. in the slag E 19006. When less abundant it may act as an interstitial mineral, the irregular grains of which coincide with the outermost zone of the melilite, or it may form acicular crystals penetrating through several melilite tables and the interstitial isotropic matter

(? glass) (pl. VIII, figs. 1 and 2). The minor constituents of the slags are calcium sulphide (oldhamite) in clusters of tiny octahedra, colourless spinel, and arborescent isotropic growths (of ?) which are typically enclosed in melilite but appear also within merwinite.

Merwinite is recognized by its high refractive index, moderate birefringence, biaxial positive character, moderately large 2V, and complex twinning. In the accompanying table there are given the optical constants of the mineral in slags E 19543, 19008 of the Geological Survey collection and of synthetic merwinite prepared at the Building Research Station. The values agree well with those determined by Belyankin and Korchemkin for merwinite from a Ural slag, but the birefringence is almost double that recorded by Larsen and Foshag for merwinite from Crestmore, the difference being due mainly to the higher value of γ in the artificial compound. The refractive indices of Crestmore merwinite were therefore studied, by the immersion method, on material supplied by Mr. F. A. Bannister, Deputy Keeper of Minerals, Natural History Museum, and values (reproduced in the table) closely comparable with those of the slag merwinite were obtained. Professor C. E. Tilley very kindly checked the values for Crestmore merwinite in his collection, obtaining α 1·706, β 1·712, γ 1·724. Coincurrently he made full determinations on the Scawt Hill merwinite, for which approximate values only were recorded hitherto, and has given me permission to publish the figures here. The new values for the natural mineral agree closely with those for the artificial compound; the higher values for the merwinite of slags E 17543 and 19008 probably indicate a material content of ferrous oxide.

TABLE I. Optical properties of merwinite from various sources.

		Blast-furnace slag.		Synthetic, prepared at the Building Research Stn.	Natural mineral.		
		E 17543. E 19008.	Ural. (±0·003).		Crestmore, determined by J. Phemister.	Scawt Hill, determined by C. E. Tilley.	Montana determined by J. H. Taylo
α	...	1·708	1·705	1·706	1·707	1·706	1·710
β	...	1·714	1·711	1·711 or 1·712	1·712	1·712	1·712
γ	...	1·728	1·724	1·724	1·725	1·724	1·718
$\gamma-\alpha$	...	0·020	0·019	0·018	0·018	0·018	0·008
2V	...	69°±2° (56°)	75°	71°±2°	67°±1°	—	70°

In the first column of the table two values of the optic axial angle are given. The lower value was observed in three broadly twinned grains; in all three one portion gave the lower angle, the other gave a normal angle.

Two sets of polysynthetic twinning are characteristic of merwinite and in sections normal, or nearly so, to the twinning the two sets of lamellae make an angle of 42½° (pl. VIII, fig. 4). The acute positive bisectrix bisects the obtuse angle between the two lamellar groups. Grains suitable for the measurement of this angle directly on the microscope stage can be found, but are not very common in thin sections of slag. Sections showing only one set of lamellae are by far the more common and the lamellae usually appear as very narrow streaks traversing the crystal or grain. Larsen and Foshag believe the mineral to be monoclinic with $\gamma = b$, $\alpha : c = 36°$, c the twinning axis, and (110) the composition-plane

cleavage is perfect parallel to (010), but is not conspicuous in thin sections lag and was observed only in sections normal to β. In crushed preparations he mineral the presence of this cleavage is, however, responsible for the large nbers of fragments which show the emergence of the acute bisectrix. Traces cleavage parallel to (100) have been noted by the writer.

The synthetic merwinite prepared at the Building Research Station is in the m of a powder which under the microscope is seen to be composed of shapeless ins up to 0·2 mm. in length, but usually considerably smaller. They are chily coated by glass and some of the larger grains contain veinlets of glass. road lamellar twinning is common and there is a tendency for some grains have edges parallel to the trace of the twinning planes. Dr. T. W. Parker es that 'the product is in effect the form stable at 1500° C. We do not know ether there are any other forms or whether merwinite decomposes at lower peratures. Similarly, we do not know whether it has a congruent melting-nt or not. Its melting-point is higher than 1500° C.' The optical properties the synthetic merwinite are given in the table. No difference beyond the ge of observational error was found between the values for the pure product that prepared in the presence of boric oxide.

n pl. VIII, figs. 5 and 6 are reproduced X-ray powder photographs, taken by F. A. Bannister, of synthetic β-$2CaO.SiO_2$ and $3CaO.MgO.2SiO_2$ prepared the Building Research Station. The spacing data are given in table II.

LE II. Spacings in Ångström units and estimated intensities of the principal lines of owder photographs of artificial merwinite and larnite (pl. VIII, figs. 5 and 6), taken with copper radiation.

Merwinite (fig. 6).		Larnite (fig. 5).	
2·94 w	1·75 vw	3·03 w	1·80 w
2·83 w	1·69 vw	2·76 s (2·751)	1·70 vw
2·73 w	1·61 w	2·69 s (2·703)	1·63 mw
2·65 s (2·646)	1·57 w	2·66 w	1·61 mw
2·41 vw	1·53 m (1·532)	2·58 vw	1·57 vw
2·30 w	1·43 vw	2·45* w	1·55 vw
2·20 w	1·39* vw	2·25 w	1·52 vw
2·16 w	1·34 w	2·18 m (2·170)	1·48 vw
2·03 w	1·32 w	2·02 w	1·39 vw
1·90 m (1·901)	1·23 vw	1·98 m (1·969)	1·37 vw
1·87 mw	1·19 vw	1·89 w	

* Unresolved doublets.

ne spacings of the strongest lines have also been measured on powder photographs taken iron radiation and are given in brackets. These lines provide a satisfactory distinction veen the two compounds and appear on relatively short exposure X-ray photographs.

n conclusion, the writer wishes to express his thanks to Professor C. E. Tilley the loan of thin sections of Scawt Hill rocks containing larnite, and to F. A. Bannister for a gift of merwinite-bearing rock from Crestmore. To these gentlemen and to the officers of the Building Research Station he ndebted for their most helpful co-operation in obtaining the data recorded in paper.

Appendix by R. W. Nurse, M.Sc.

Note on the melting relations of Merwinite.[1]

From the constancy of the figures given by Dr. Phemister for the optic constants of merwinite, it is almost certainly a pure compound; it is therefo to be expected that it should be found in the system CaO–MgO–SiO_2. A fe experiments carried out by the writer in the course of work at the Buildi Research Station show that the synthetic merwinite, the method of preparati and optical properties of which are described in Dr. Phemister's paper, decor poses at 1590° C. into melt and a phase which resembles $2CaO.SiO_2$, except th the refractive indices are lower (α 1·708, γ 1·735) and the axial angle is ve small, being nearly uniaxial. When examined under the microscope in polishe sections, with vertical illumination, the decomposition product is etched b HF vapour, 10 % $MgSO_4$ solution, and alcoholic nitric acid solution, reactio which are characteristic of $2CaO.SiO_2$, whereas merwinite is not etched by 10 $MgSO_4$. From the limited data available it may be concluded that merwini does in fact occur in the system CaO–MgO–SiO_2 as an incongruently meltin compound.

While a re-examination of Ferguson and Merwin's diagram in the regio adjacent to the monticellite and åkermanite primary phase fields would b necessary to confirm that merwinite can occur as a primary phase in the terna system, there is a strong possibility that it does do so in that part where fin melting temperatures are below 1590°. The compositions shown as having be examined by Ferguson and Merwin in the construction of their ternary diagra include only a few in this area.

As a matter of interest, blast-furnace slags melt completely at temperatur lower than that of the decomposition temperature of merwinite, and the latt can therefore occur as a phase in contact with melt in blast-furnace slag systen

Explanation of Plate VIII.

Photomicrographs of merwinite in blast-furnace slags (figs. 1–4).

Fig. 1. E 17543. Needles of merwinite in stout tables of melilite which contain arboresce growths of isotropic material spreading from the *c*-axis towards the pinakoidal fac Ordinary light. ×50.

Fig. 2. E 17543C. Needles of merwinite in a slag composed mainly of melilite. Nicols nea crossed. ×40.

Fig. 3. E 19008. Intergrowth of merwinite in a thick table of melilite which shows the ba cleavage. Nicols crossed. ×30.

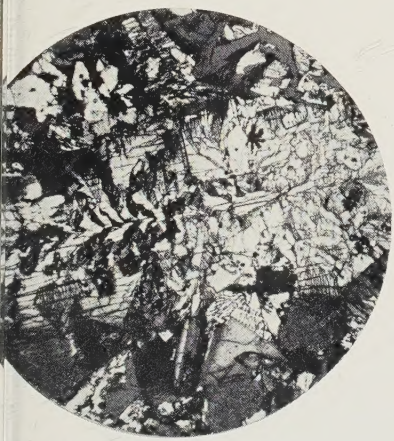
Fig. 4. E 19008B. In the centre of the photograph a crystal of merwinite shows the two s of lamellar twinning inclined at 42½°. Nicols crossed. ×60.

Figs. 5 and 6. X-ray powder photographs of artificial larnite, β-$2CaO.SiO_2$ (fig. 5), a artificial merwinite, $3CaO.MgO.2SiO_2$ (fig. 6), taken with unfiltered copper radiati and with the same cylindrical camera diameter 6 cm. Actual size.

[1] Communicated by permission of the Director, Building Research Station.

1

2



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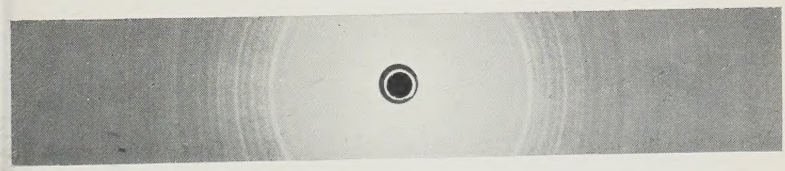

5

6

J. Phemister: Merwinite in Slags.